CHAPTER 1

INTRODUCTION

This thesis, Searching for pulsars with LOFAR, describes my work on the first pilot radio pulsar searches using the new Low Frequency Array (LOFAR) telescope (van Haarlem et al., 2013; Stappers et al., 2011). In this chapter I will briefly introduce some of the prerequisites: what are radio pulsars and how they relate to neutron stars, how radio pulsar searches are conducted, why finding more pulsars is scientifically important, and what makes LOFAR a unique and powerful instrument for pulsar surveys.

1.1 RADIO PULSARS

1.1.1 DISCOVERY

The first pulsar was discovered by Jocelyn Bell in 1967. Bell, then a PhD student with Antony Hewish at the University of Cambridge, was working on observations of inter-planetary scattering when interference-like signals appeared in their observations. The radio telescope they used — or rather, built with their bare hands and then used — was a large array of 2048 dipole antennas. Operating as a “phased array”\(^1\) this instrument observed several large fields-of-view simultaneously, scanning the sky as the Earth rotated. Crucially, the array was equipped with a, for the time at least, high-time-resolution receiver system that had a time constant of 0.1 s. The first pulsar

\(^1\)Here we use the term “phased array” to denote a collection of radio antenna elements that are “coherently added” (i.e. added in phase), to produce a much larger equivalent collecting area.
signals appeared as “scruff” (Bell’s own words) on the chart recorder output. Because the signal was observed to be at a fixed right ascension and declination (i.e. it followed sidereal time) it clearly did not originate from Earth. Further investigation showed that the emission was pulsed at an extremely stable period so a non-astrophysical origin seemed possible. The Cambridge group was able to exclude spacecraft, radar and reflections of man-made signals off of the Moon as possible origins because parallax measurements showed the signals were emitted far outside of the Solar System. Extra-terrestrial signals were also briefly considered as a potential source (the source even acquired the humorous name LGM-1, for “Little Green Men”). Since no Doppler shift other than that caused by the Earth’s motion around the Sun could be measured for the pulses, this latter explanation was deemed unlikely. The swift detection of three more pulsars made it clear that a new type of astrophysical source had been discovered. The discovery of the first pulsar, now known as PSR B1919+21, was announced in Nature by Hewish et al. (1968). The extremely stable period of the observed pulsations pointed to a massive emitter and the extremely short duration of the pulses pointed towards a small object. While the discovery paper already mentions white dwarfs or neutron stars as possible sources, it subsequently (and relatively quickly) became clear that neutron stars were the likely origin.

1.1.2 IDENTIFICATION AS NEUTRON STARS

Neutron stars had until the discovery of pulsars only been theoretically predicted, not observed (or at least not identified as such, see below). Shortly after the discovery of the neutron (Chadwick, 1932) the idea that stars consisting of neutrons could be formed from a “normal” star in a supernova was first proposed by Baade & Zwicky (1934). The structure of such a star was not described, however. The first models of neutron star structure were derived by solving the general relativistic field equations for static fluids (Tolman, 1939) and for the special case of a cold Fermi gas (Oppenheimer & Volkoff, 1939). For several decades following this initial theoretical work, no observations could positively be ascribed to neutron stars. Wheeler (1966) considered super-dense stars and specifically investigated whether the Crab nebula, a known supernova remnant, could be powered by a neutron star. A year later, Pacini (1967) suggested that a neutron star would be born with a large reservoir of rotational kinetic energy. Combined with a dipolar magnetic field a rotating neutron star would be able to power the Crab nebula through electromagnetic dipole radiation.

In the discovery paper of radio pulsars (Hewish et al., 1968), white dwarfs and neutron stars were suggested as possible sources of the observed pulsations. These objects were both small enough to satisfy light crossing time arguments and massive enough
1.1. Radio Pulsars

to possibly explain the extreme stability of the observed pulsations. Several mechanisms involving neutron stars and white dwarfs were considered. Processes involving white dwarfs were too slow to explain the short periods observed in pulsars however (Manchester & Taylor, 1977). The discovery of pulsars near the centers of the Vela X (Large et al., 1968) and Crab nebulae (Staelin & Reifenstein, 1968) made clear the link between supernovae (and their massive progenitor stars) and pulsars. Gold (1968) proposed that pulsars are rotating neutron stars and predicted their pulse periods should increase over time due to magnetic breaking; this matched observations.

Searches for optical pulsations succeeded in detecting a source whose rapid pulsations matched those of the Crab radio pulsar (Cocke et al., 1969). This source had been identified as the object left over from the supernova explosion that formed the Crab nebula (Baade, 1942; Minkowski, 1942). To this day, the Crab remains one of only a handful of pulsars with detectable optical pulsations.

1.1.3 Propagation Effects in the Interstellar Medium

Relevant to radio observations of pulsars are not just the intrinsic properties of the pulsars themselves but also the properties of the intervening medium. Traversal of the interstellar medium (ISM) affects the pulsar signal in several ways: i. signals are received later at lower observing frequencies through a process called dispersion; ii. the phase of the signal is affected by irregularities in the ISM, which causes scintillation (intensity modulation with time and observing frequency); iii. scattering causes the signal to arrive at the observer along different paths, effectively convolving the pulse shape with an exponential decay function; iv. the polarization angle of the signal is affected by Faraday rotation caused by the line-of-sight Galactic magnetic field. All of these effects have strong frequency scalings (e.g. scattering delay scales approximately as $\nu^{-4}$ and hence they are a very important consideration (and sometimes a major limitation) at low observing frequencies like those observed by LOFAR (10 − 240 MHz). These effects are treated in more detail in Lorimer & Kramer (2005) and references therein.

Dispersion in particular is an important, and correctable effect when performing surveys to discover new pulsars. In fact, the dispersive delay of the signal across a broad observing band must be compensated for in order to detect any but the brightest and nearest pulsars. The effects of dispersion were already evident in the very first pulsar observations. Hewish et al. (1968) described the frequency sweep detected in the pulsar signal and attributed it to a propagation effect in the cold ionized plasma of the ISM. The propagation speed of radio signals in this plasma is frequency dependent, with higher frequencies propagating faster. The delay in arrival time $\Delta t$ this causes
between observing frequencies \( f_1 \) and \( f_2 \) is given by:

\[
\Delta t \simeq 4.15 \times 10^6 \text{ ms} \times (f_1^{-2} - f_2^{-2}) \times \text{DM} \text{ ms},
\]

with \( f_1 \) and \( f_2 \) in MHz and the dispersion measure (DM) given in pc cm\(^{-3}\). The DM is a measure of the column density of free electrons along the line-of-sight and is given by:

\[
\text{DM} = \int_0^d n_e \, dl,
\]

where \( d \) is the distance through the plasma and \( n_e \) the free electron density. To maximize the signal-to-noise ratio of the detected pulses the frequency sweep needs to be taken into account when adding the signal over the observational bandwidth. The DM can be used to estimate the distance to pulsars given a model for the free electron density of the Galaxy (e.g. the NE2001 model Cordes & Lazio, 2002).

### 1.1.4 Pulsar Science

Since their discovery and identification as neutron stars over 4 decades ago radio pulsars have continually been studied. Their nature as compact and very massive objects with large magnetic fields creates circumstances that cannot be recreated on Earth in a laboratory. The observation of pulsars thus allows us, otherwise unachievable, access to exotic physics. Pulsars can furthermore be used to study other objects that they might be orbiting and the conditions in the interstellar material along the line-of-sight from the pulsar to the observer. Understanding the pulsar population also sheds light on stellar evolution as pulsars are one of its endpoints. In this section we will give a short and by no means exhaustive description of some the highlights of pulsar science.

After their initial discovery pulsars that go on to be studied in depth will undergo so-called pulsar timing (see e.g. Lorimer & Kramer, 2005). This is a process whereby the pulse arrival times are tracked and a model is created describing their evolution over time. The timing models thus created can grow to be fantastically precise and need to take into account all physical effects affecting the pulse time-of-arrivals (TOAs). They include everything from the rate at which the pulsar’s rotation slows down, its precise position on the sky, any binary motions it may have, General Relativistic effects caused by massive binary companions, to a complete models of the masses in the Solar System. Repeated observations, over in some instances decades, allow increasingly precise models to be constructed and therefore increasingly subtle effects to be measured.
One of the theories amenable to testing through pulsar observations is General Relativity. The first pulsar discovered in a binary system has another neutron star as its companion (Hulse & Taylor, 1975). In this binary, known after its discoverers as the “Hulse-Taylor binary”, the component masses and the parameters of the binary orbit could be measured to such precision that the shortening of the orbit through gravitational radiation could first be measured (Taylor & Weisberg, 1982). The discovery of the Hulse-Taylor binary and the tests of General Relativity that it allowed was awarded the 1993 Nobel Prize in Physics. The discovery of the Double Pulsar (Lyne et al., 2004) allowed the most stringent tests of General Relativity to date (Kramer et al., 2006b). Another system that can be used to test General Relativity was recently discovered and contains a two solar mass pulsar along with a light white dwarf (Antoniadis et al., 2013). The first triple system containing two white dwarfs and a pulsar, PSR J0337+1715, was discovered in 2012. This discovery came after hints were found that triple systems containing pulsars should exist based on the existence of an MSP, PSR J1903+0327, in an eccentric binary that could be explained as the result of the disruption of a triple system (Champion et al., 2008; Portegies Zwart et al., 2011). The PSR J0337+1715 triple system holds the promise of being a laboratory to test the Strong Equivalence Principal of General Relativity (Ransom et al., in prep).

Furthermore there are currently efforts to detect gravitational radiation directly by measuring how a passing wave distorts the signals of a large set of well studied pulsars. The largest effort of this type is the International Pulsar Timing Array (IPTA, Hobbs et al., 2010).

It was long expected that MSPs are formed through the accretion of material from a binary companion onto an otherwise garden variety pulsar (Bhattacharya & van den Heuvel, 1991). In this recycling scenario there should thus be a link between X-ray binaries and MSPs. A few years ago an MSP, J1023−0038, was found that was unobservable as a radio pulsar whilst showing evidence of an accretion disk only several years prior. It was thus called the “missing-link” pulsar (Archibald et al., 2009). More recently, the identification of the newest accreting millisecond pulsar, IGR J1824−2452, with the previously known radio pulsar J1824−2452I (in the globular cluster M28) gives us the first instance where we’ve observed both accretion powered emission (X-ray bursts, etc.) and rotation powered (spin-down) emission from the same source (Papitto et al., 2013a).

Before extra-solar planets were found in optical observations they were first detected orbiting the pulsar PSR J1257+12. This pulsar is orbited by at least three planets (Wolszczan & Frail, 1992). Recently also an MSP was found that is orbited by a “Diamond planet” (Bailes et al., 2011, a dense, low-mass carbon companion). This system also sheds light on how MSPs that were presumably formed in a binary could end up as isolated MSPs. Pulsar timing can also be used closer to home: the masses of
the planets in our Solar System can also be measured accurately as was demonstrated by the second most precise measurement of Jupiter’s mass (Champion et al., 2010), the most precise measurement was performed using the Galileo spacecraft in orbit of Jupiter. This technique can also discover planets in the outskirts of our Solar System (or place limits on the presence of such trans-Neptunian objects).

Pulsars also provide a laboratory in which to study the properties of dense, neutron-rich matter and the equation-of-state (EOS) of neutron stars. The discovery of a two-solar-mass MSP, PSR J1614−2230, placed very strong constraints on these properties and the EOS of neutron stars (Demorest et al., 2010). Rapidly rotating neutron stars can also be used to constrain the neutron star EOS. The current fastest-spinning pulsar, J1748−2446ad, rotates at 716 Hz (Hessels et al., 2006).

Though much of the high-profile pulsar science from the last decade has been driven by pulsar discoveries and follow-up timing of these (this is the overarching motivation for the searches conducted as part of this thesis) significant results have also been gleaned from long-term studies of known pulsars. For instance, using their database of more than 30 years of pulsar arrival times, Lyne et al. (2010) have shown a correlation between timing noise (a non-predictive wander of the pulse phase over timescales of months to years) with changes in the pulse profile morphology. This investigation was spurred by the earlier discovery that some pulsars are intermittently active on week to month timescales and show a different spin-down rate when they are active/inactive (Kramer et al., 2006a). Lastly, another recent finding that radio pulsar mode switching, a profile-switching effect known from the early days of pulsar science, is also correlated with switches in the X-ray emission mode (Hermsen et al., 2013) is yet another novel insight. Together these results provide important information on the famously enigmatic pulsar radio emission mechanism.

1.2 RADIO ASTRONOMY

1.2.1 Earliest days

Before undersea cables and satellites were introduced, communication across the Atlantic used short-wave radio signals, pioneered by inventor Guglielmo Marconi and others. The American telecom giant Bell employed physicist and engineer Karl Guthe Jansky to investigate possible sources of interference with short-wave radio communication. At the Bell Laboratories site, Jansky built and operated a large directional antenna with which he scanned the horizon. He quickly identified thunderstorms, both near and distant, as a source of interference. In 1932 he identified another signal,
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...a soft, persistent hiss that he attributed to the Sun. Detailed investigation showed however that this signal did not in fact track the Sun, but rather a position fixed with respect to the stars (i.e. locked to sidereal time). Jansky derived a position for the source of the static of approximately 18 hours in right ascension and −20 degrees in declination — the first cosmic radio source was found. Jansky identified the center of the Milky Way as the likely source — see Jansky (1933b) and Jansky (1933a). Although Jansky was the world’s first (accidental) radio astronomer, and though his discovery reached the front page of the New York Times, it would nonetheless take several years before radio astronomy really took off as a new scientific field.

Jansky wanted to continue his studies, but he did not get to build the larger radio antenna he proposed to Bell Laboratories. Rather, he was re-assigned to other tasks and it would take another pioneer to move radio astronomy forward. An electrical engineer by training, Grote Reber was greatly inspired by Jansky’s discovery and wanted to work on radio astronomy. He tried to get a job with Bell but did not succeed, however. Instead, in 1937 he built a 9-meter dish of his own in his backyard in Wheaton, Illinois, the United States. Attempts to reproduce Jansky’s results failed at 3300 MHz and 900 MHz but at the lower observing frequency of 162 MHz Reber finally did detect the presence of the Milky Way (Reber, 1940). Contrary to Reber’s expectation that higher radio observing frequencies would be more productive, lower observing frequencies were in fact more rewarding because of the non-thermal nature of the emission he was detecting. A few years later Reber produced a map of the distribution of this radiation in Reber (1944). It were these results of Grote Reber that reached the Netherlands during the Second World War.

1.2.2 DUTCH RADIO ASTRONOMY

WITH low elevations (it’s the “low countries” after all) and the prevalence of dreary weather, the Netherlands is not the ideal location for an optical telescope. In stark contrast to the optical regime\(^2\), however, the Netherlands has a long tradition of radio astronomical research facilities in the country and hosts two world-class observatories: the Westerbork Radio Synthesis Telescope (WSRT) and the Low Frequency Array (LOFAR). In this section I will briefly sketch the history of Dutch radio astronomy. A more complete overview of early Dutch radio astronomy can be found in van Woerden & Strom (2006) and the Dwingeloo telescope’s history in van Woerden & Strom (2007).

\(^2\)Note however that the Netherlands does have a strong tradition of building instruments for optical telescopes located in other, less cloudy countries.
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Dutch radio astronomy started with the realization by Jan Hendrik Oort that, if there was a detectable spectral line in the radio band, then it would not be affected by interstellar extinction through dust. Oort, by then a professor at the Sterrewacht Leiden (the Leiden Observatory), had previously worked on the structure of the Milky Way and observed differential rotation (see Oort, 1927). The optical observations that were used to obtain this result were only possible out to a distance of a few kilo-parsecs however, not enough to determine the global structure of the Milky Way. By mapping a spectral line not affected by interstellar extinction the structure of the Milky Way could be determined. In 1944 Oort invited the Utrecht student Hendrik Christoffel van de Hulst to a colloquium on radio waves from space. At that colloquium van de Hulst presented a paper about the possible origin of the previously detected radio signals and further suggested that a hyperfine transition at 21 cm (1420 MHz) in neutral Hydrogen atoms (HI) could possibly be observed. This line corresponds to a flip in the relative spins of the proton and electron in HI. Van de Hulst’s presentation has been called the birth of Dutch radio astronomy and the HI spectral line remains a key aspect of radio astronomical research today. Even during the war, it lead Oort to start planning a radio observatory in the Netherlands.

Although the government was interested, no funds were available directly after the war to construct a dedicated radio telescope as envisioned by Oort. A few years after the war, in 1948, attempts to observe the HI line were started by Stichting Radiostraling van de Zon en Melkweg (SRZM, Foundation for Radio Emission from the Sun and Milky Way) — with observations already ongoing, SRZM was only officially founded in 1949.3 A salvaged German Würzburg radar was put to use at Kootwijk with both Philips and the state post, telegraphy and telephony company (PTT) contributing expertise. Meanwhile a group at Harvard were also trying to detect the HI line. Only weeks after H.I. Ewen and E.M. Purcell at Harvard succeeded in detecting the HI signal the first Dutch detection was made on May 11, 1951. Both detections were published in the same edition of Nature: Ewen & Purcell (1951) and Muller & Oort (1951). Starting in 1952 the Kootwijk Würzburg was used to map out the HI distribution of the Milky Way. The first Dutch HI survey (van de Hulst et al., 1954) also resulted in the measurement of the Galactic rotation curve (Kwee et al., 1954). An important conclusion from this measurement was that the Galactic rotation curve flattened out beyond 3 kilo-parsec. A second more detailed survey was published in Muller & Westerhout (1957). At about the same time solar observations were performed from Nederhorst den Berg.

A 25-meter dish proved too expensive to build directly after the Second World War but 3SRZM would go on to become the current ASTRON — Netherlands Institute for Radio Astronomy, where much of the work presented in this thesis was completed.
by the early 1950s funds were again available. In 1951 the Werkspoor company was commissioned to design and build a dedicated radio telescope. The design was completed in 1954 and construction started at a sparsely populated site near Dwingeloo, in the province of Drenthe, soon after. Although not finished yet, the telescope’s first observations were made in November 1955 when the Moon occulted one of the brightest known radio sources. Inaugurated in April 1956, the Dwingeloo telescope’s regular astronomical observations started in July that year. It was briefly the largest operational radio dish in the world, soon to be dethroned by the Lovell Telescope in the United Kingdom. The Dwingeloo telescope initially had receivers sensitive to the HI line at 1420 MHz and in the continuum near it. Among the first scientific observations made with the Dwingeloo telescope were a 21.6 cm continuum survey (Westerhout, 1958) and a quick survey of the sky resulting in a catalog of 80 discrete sources.

Highlights of research with the Dwingeloo telescope include the discovery of so-called high-velocity clouds in a search for neutral HI clouds at high latitudes (Muller et al., 1963). Later a large survey for this type of object was performed (Hulsbosch & Wakker,
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The Dwingeloo telescope also produced an accurate survey of Galactic HI, the Leiden-Dwingeloo Survey, which was published by Hartmann & Burton (1997). The discovery of two galaxies obscured by our Milky Way, Dwingeloo I and II, in the Dwingeloo Obscured Galaxies Survey (Burton et al., 1996) also serves as a lasting legacy and namesake for the telescope. Decommissioned in 1999, after having been used for scientific observations for more than 4 decades, the Dwingeloo telescope is now a monument — part of Dutch industrial heritage. The telescope is currently run by volunteers from CAMRAS.

The Dwingeloo telescope had modest spatial resolution of 36 arcmin at 21 cm (see e.g. van Woerden & Strom, 2007). Around the time it became operational it was clear that better localization and resolving power were needed in radio to be able to identify the radio sources with previously known objects and to better understand their physics. Higher spatial resolution is achievable through radio interferometry, a technique first demonstrated in the 1940s. Ryle & Vonberg (1946) performed measurements towards a sunspot using a two element interferometer and McCready et al. (1947) used a coastal radar installation and the sea as a reflector to create an interferometer that could localize sunspots. The first preliminary design for the next Dutch radio telescope, targeting a resolution of 1 arcmin, was produced in 1958 (another initiative of Oort, like the Dwingeloo telescope before it). While the design for this array would go through several iterations the first version was based on the Mills cross interferometer in Australia (Hill et al., 1958). Cooperation with Belgium was sought because the observatory would be too expensive for the Netherlands alone — one design iteration of the so-called Benelux Cross Antenna involved about 100 30-m dishes and at least one 70-m dish (see e.g. Raimond, 1996)! The advent of Earth-rotation aperture synthesis (Ryle, 1962) allowed the design to be simplified; the East-West and North-South aligned arrays of a cross type interferometer could be replaced with a single East-West array using the Earth’s rotation with respect to the sky to gradually fill in the synthesized telescope’s aperture. The number of dishes could be reduced to about 30 while still providing the desired spatial resolution at the cost of slower observations with lower time resolution.

While Belgium participated in the preparatory phase of the project it became clear by the early 1960s that it would not invest in the construction of the new observatory. The Dutch funding was available so a simpler version of the linear array was built at a site near the village of Westerbork (about 25 km away from the Dwingeloo telescope). The final Westerbork Radio Synthesis Telescope design comprised 12 dishes, two of which were moveable along a rail track. Construction started in 1965 and by spring 1969 test observations with part of the array were being performed, with real observations having been conducted by late 1969.

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See [http://www.camras.nl](http://www.camras.nl)
Figure 1.2: One of the Westerbork Synthesis Radio Telescope’s 25-meter dishes. The linear, East-West array includes 14 such dishes, spread over 3 km.
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following June the next year. Initially only receivers for continuum observations near 21 cm were available, but later upgrades would provide other capabilities at other wavelengths. In 1975 a plan was made to extend the WSRT from an array of 1.5 km to 3 km and to add an extra 2 moveable antennas. More information about the early history of WSRT and an account of its observational capabilities over the first 25 years of its operation can be found in Raimond (1996).

While WSRT was originally designed and built to do imaging observations with backend systems not suited for observations of pulsed radio emission, some pulsars were nonetheless observed. The telescope participated for example in the identification of the original millisecond pulsar (Backer et al., 1982), and the well-known millisecond pulsar PSR J0218+4232 was serendipitously discovered in a WSRT image (Navarro et al., 1995). By the late 1990s, the Pulsar Machine (PuMa, Voûte et al., 2002) was installed at Westerbork. Using PuMa and its successor (PuMa-II, Karuppusamy et al., 2008) WSRT was finally able to observe pulsed radio emission. Examples of pulsar work with WSRT are studies of sub-pulse drifting in a large number of pulsars (Weltevrede et al., 2006a) and the discovery of single dispersed pulses potentially from neutron stars in M31 (Rubio-Herrera et al., 2013).

After 40 years of active service, the WSRT is still a world class observatory, which soon will be upgraded with the Apertif (for Aperture Tile in Focus) front-end system (Verheijen et al., 2008; Oosterloo et al., 2010). In this upgrade, the Westerbork horn receivers will be replaced by so-called phased-array feeds (PAFs). These phased arrays are located in the focal plane of each telescope. With these PAFs, 37 independent beams are created for each WSRT dish, covering over 8', square degrees of sky, with 300 MHz of bandwidth tunable in the 1.0–1.7 GHz band. Apertif will allow for sensitive, efficient surveys for HI and OH lines to larger redshifts than currently possible. That improved mapping over a larger volume of neutral hydrogen is expected to increase our knowledge of galaxy evolution. Because of Apertif’s wide bandwidth the line surveys will also shed light on continuum emission associated with, e.g., star formation and active galactic nuclei. Real-time pulsar and transients surveys are also planned with Apertif. With the new ARTS (Apertif Radio Transient System) back-end that is currently being built, the increased bandwidth will improve Westerbork’s ongoing pulsar research; while its wide field allows for surveys of fast transients such as the Rotating Radio Transients (RRATs) or the extragalactic bursts, that are the most sensitive in the world.

While a lot of early radio astronomy was done at frequencies below several hundreds of MHz, e.g. the discovery of pulsars at 81 MHz (Hewish et al., 1968), it was clear in the late 1980s and early 1990s that a new low-frequency radio observatory was both scientifically interesting and technically feasible.
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1.2.3 LOFAR

The low-frequency end of the radio window has remained a relatively under-explored regime, especially at high angular and time resolution. It had become clear that steep spectrum pulsars and sources with inverted spectra (through synchrotron self absorption or free-free self absorption) and high red-shift galaxies needed to be studied at low frequencies. This provided the case for building a new observatory. Early plans for what was to become the square kilometer array (SKA) were being made.

LOFAR was proposed as one of the international telescopes that would be used to develop the technologies needed for the SKA. It would also be a sensitive observatory in its own right. At low frequencies a dish based design would be impractical because of the required size. Indeed arrays of connected antennas, so-called phased arrays, had been used in the past (see e.g. the telescope that discovered pulsars). It was suggested at ASTRON that using a phased array would provide the required sensitivity and angular

Figure 1.3: LOFAR LBA antennas in the LOFAR core near Exloo, Drenthe, The Netherlands.
resolution. Technology had progressed to the point that such a telescope could be built for the low frequency radio regime which, unlike its predecessors, could have fully (digitally) steerable beams. When funds from the Dutch government became available to build LOFAR, but with the stipulation it be built in the Netherlands, the international LOFAR project split. The other offshoots of the original LOFAR project are the Long Wavelength Array (LWA) in the USA and the Murchinson Widefield Array (MWA) in Australia.

The LOFAR array consists of a series of phased-array antenna stations that are combined to form a large interferometer operating at low radio frequencies. Each station has both Low Band Antennas (LBAs) used for observations at 10–100 MHz and High Band Antennas (HBAs) for 110–240 MHz. Each individual antenna in LOFAR is a crossed dipole that allows full polarization measurements, and which in the case of the high band are combined into "tiles", each containing 16 antennas. At each station the LBA antenna (or HBA tile) signals are digitized, formed into one or multiple station beams, and sent across to the central correlator, currently an IBM Blue Gene/P.
supercomputer, via dedicated fiber optical network links. The Blue Gene then cross-correlates the station signals or performs beam-forming (or both simultaneously). The former mode is used to do aperture synthesis imaging with dump times as short as $\sim 1$ second, while the latter mode provides sub-millisecond time resolution for single-pixel observations.

The array is centered around a site in Exloo, Drenthe, The Netherlands. It is there that the densest part of the array, the so called Core, is located. The core contains 24 LOFAR stations, 6 of which lie on an artificial island termed the “Superterp” (Terp is Dutch for a very large mound of earth, artificially raised to protect against water).

1.3 RADIO PULSAR SURVEYS

THOUGH roughly 2000 radio pulsars are now known, including a few hundred millisecond pulsars, searches for new radio pulsars remain a driving force in the field, with many high-profile discoveries in the last decade (see Section 1.1.4 for some highlights). Besides better understanding the total Galactic pulsar population and its characteristics the major scientific driver for these searches is finding ever better laboratories for understanding exotic stellar evolution, gravitational theories, and dense matter physics. For instance, the prospect of finding an extremely rare pulsar-black-hole binary system — perhaps the ultimate precision laboratory for testing strong gravity — is one of the high-profile justifications for an all-sky SKA pulsar survey that will bring us close to a full Galactic census of the population.

The nature of pulsar emission, both in terms of its intrinsic brightness and the short timescale variabilities involved, put unique requirements on observatories used for pulsar observations. To successfully observe pulsars, a recording system is needed that is capable of high time resolution (at least sub-millisecond), large bandwidth (typically a fractional bandwidth of $10-50\%$), and relatively high spectral resolution (100s-kHz channels) for correcting dispersive delay. For the majority of radio telescopes involved in pulsar observations such a recording system consists of dedicated hardware known as a pulsar backend. Once recorded, post-processing data of known pulsars does not require large amounts of computation. The discovery of new radio pulsars on the other hand requires a large amount of data storage (in some case petabytes) and large computational resources (millions of core hours). To cover a significant area of sky many individual telescope pointings are needed, each of which must be searched for pulsar signals with an unknown period, DM, and quite possibly an orbit with

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5Thus far we have detected less than 10% of the potentially observable (i.e. beamed towards us) pulsars in our Galaxy.
unknown parameters. In this section we describe a typical pulsar search and some relevant considerations.

1.3.1 A TYPICAL PULSAR SEARCH

The first step in data processing for a pulsar survey is to search for interference (RFI) or other data problems. In this process, entire frequency channels may be flagged because they are dominated by interference, which is distinguishable from astronomical signals because human transmissions are generally bright and narrowband. Further, the signal strength with time is checked for very bright, short-duration interference bursts, especially those that show no dispersive delay from the ISM. RFI excision is not limited to the time-domain; periodic interfering signals in the power spectra are also flagged. Such periodic signals are known to be interference because they appear at zero DM and towards different parts of the sky. During all these steps, however, care must be taken to ensure that interesting astronomical signals are not also rejected.

To reach the telescope, pulsar signals need to traverse interstellar space, where they acquire a frequency sweep because of propagation effects in the cold plasma of the interstellar material. As was described in Section 1.1.3, this sweep is parametrized by the DM and needs to be compensated for to observe all but the brightest, relatively nearby pulsars. Since in a blind survey the positions and distances of potentially detectable pulsars are unknown, their DMs are unknown and the pulsar search therefore involves a search over a range of trial DMs. Models of the free electron content of the Galaxy can be used to inform the range of DMs to search. Typically one calculates the maximum DM for a given line-of-sight in the Galaxy and then searches a DM range up to twice this value, in order to ensure full coverage. This range is sometimes extended much further to gain sensitivity to extra-galactic pulsars or fast radio transients. For a globular cluster containing known pulsars, it is possible search only a small range of DMs around the known cluster DM.

The search then iterates over all trial DM values. After removing the dispersion sweep associated with a certain DM, a process called dedispersion, the full available bandwidth is summed and the resulting time-series is searched for pulsar signals. These signals can be found by looking for individual bright pulses; this technique is known as a single pulse search. The discovery of PSR B1919+21 was made by inspecting plots of signal strength over time (Hewish et al., 1968) and is therefore an example of what we would now call a single-pulse search. Soon after this first discovery it was realized that the highly stable period of a pulsar’s emission made it detectable in a so-called periodicity search (e.g. see Burns & Clark, 1969). These periodicity
1.3. RADIO PULSAR SURVEYS

searches, conducted using Fast Fourier Transforms of the dedispersed time-series, are a staple of pulsar searches because they are sensitive to pulsars whose individual pulses are not bright enough to be directly detected. For a while single-pulse searches were foregone completely, but that changed with the discovery of Rotating Radio Transients (McLaughlin et al., 2006) which only emit highly intermittent radio pulses. This discovery made it clear that there is a population of neutron stars that are only detectable through their single-pulse emission (at least at the current sensitivities of our telescopes) and single-pulse searches became a standard part of pulsar survey processing again. The importance of single-pulse searches was again underlined when a single highly dispersed pulse of plausibly extra-galactic origin was detected (Lorimer et al., 2007). All modern radio pulsar searches thus run both single-pulse and periodicity searches and look for both pulsars (in all their stable and intermittent forms) as well as more generic fast radio transients.

After all DMs have been searched the list of pulsar candidates produced by the periodicity search is prioritized and the most promising candidates are inspected. Because surveys can consist of a large number of observations the number of candidates may be in the millions and the candidate selection may be further automated. For the single-pulse search, diagnostic plots are also made and are inspected for the presence of interesting signals (see for example Figure 3.6 of Chapter 3). The most interesting candidate pulsars (or RRATs) are then scheduled for confirmation observations. While a single re-detection is enough to confirm the reality of the pulsar candidate, generally monthly observations are performed over the course of a year in order to constrain the pulsar’s rotational and astrometric parameters.

1.3.2 SURVEYS WITH LOFAR

For blind pulsar surveys, i.e. those not specifically targeting systems suspected of harboring pulsars, a large field-of-view is a great advantage. All things being equal, a larger instantaneous field-of-view allows more sky to be surveyed in less time or to use the same amount of time to observe each sky position longer. Because LOFAR’s simple antennas, dual-polarization cross dipoles, are sensitive to most of the sky, unlike telescope dishes, it is possible to combine their signals such that a large part of sky is covered at once. The High Time Resolution Universe pulsar survey uses a 13-beam receiver on the Parkes telescope for an instantaneous field-of-view of 2.3 square degrees (Keith et al., 2010) while LOFAR is capable of much larger fields-of-view (e.g. 75 square degrees for the LPPS pulsar survey reported in Chapter 3 of this thesis). Most of the propagation effects described in Section 1.1.3 more strongly affect low-frequency radio observations. Dispersion is strongly dependent on observing fre-
quency $\nu$ with the dispersive delay $d t$ scaling as $d t \propto \nu^{-2}$ (see e.g. Lorimer & Kramer, 2005). For sources of known DM the dispersive smearing can be removed completely using coherent dedispersion. During a pulsar survey, the DMs of the potential discoveries are unknown and therefore the technique cannot be used because it is too computationally intensive and requires the full amplitude and phase of the signal (typically only the total intensity, i.e. “Stokes I”, is recorded in a pulsar survey in order to reduce the data rate). Instead, the data is dedispersed incoherently, that is to say by adding appropriate time delays to each frequency channel so that the signal arrives at the same time across the entire band. By using more frequency channels of smaller bandwidth the dispersive delay in each channel can be kept to a minimum. LOFAR has the capability to make many small frequency channels (typically thousands of 12-kHz channels) and enough compute power is available to process them. An advantage of the stronger dispersion effects at low radio frequencies is that they make it easier to distinguish between local broad-band RFI, which is not frequency swept, and signals of nearby pulsars with low DMs, because even a low DM causes an appreciable dispersive delay that is lacking in the case of RFI. Scattering is even more strongly dependent on observing frequency with the scattering timescales increasing towards lower frequencies as $\nu^{-4.4}$ (see e.g. Lorimer & Kramer, 2005). This unfortunate effect cannot not be mitigated, but is dependent on the exact layout of the scattering material along the line-of-sight. It does not affect each line-of-sight equally and can change by an order of magnitude, so along some lines-of-sight LOFAR may still be able to reach deeper than expected from the $\nu^{-4.4}$ relation. Another complication is the fact that the sky background temperature increases towards lower frequencies as $\nu^{-2.6}$ (Lawson et al., 1987) adversely affecting detectability of pulsar signals. Here as well it must be noted that the effect is dependent on the location that is surveyed as the Galactic plane has the highest background temperatures. Thus, LOFAR surveys starting a few degrees off the Galactic plane are the most competitive with other ongoing efforts. Because LOFAR is a large observatory operating at frequencies that are not explored to the same extent as higher radio frequencies the potential for new discoveries is great.

1.4 THIS THESIS

The work in this thesis is based entirely on radio pulsar searches, some targeted and some blind. These searches were performed predominantly with LOFAR, and in one case with the Green Bank Telescope (GBT). Chapter 2 is about a targeted pulsar search towards 4 sub-dwarf B (sdB) binary systems using the GBT. These stars have been observed with a wide variety of binary compan-
ions and prior optical observations of our sample had found evidence for compact, massive companions in these sdB binaries. Based on the data reduction and analysis that I performed we were able to place strict upper limits on the presence of any pulsed emission from these systems.

During the commissioning period of the telescope, the LOFAR Pulsar Working Group performed two pulsar surveys, the full results of which are presented in this thesis. The first survey, called the LOFAR Pilot Pulsar Survey (LPPS), is a survey that profits from LOFAR’s large field-of-view to efficiently perform a fast, shallow survey of the Northern Celestial Hemisphere. During the early stages of this project I developed and contributed to the testing of the LPPS search pipeline. Using the final version of this pipeline I searched all LPPS survey data presented in this thesis. In the LPPS survey data we re-detected 65 pulsars of which one was an independent discovery, that had not yet appeared in the literature and knowledge of which we did not use during our search (the pulsar had recently also been found in a GBT survey at 350 MHz). To check the efficiency of our pulsar search I manually checked the positions of previously known pulsars that were not picked up in the search, resulting in the re-detection of 9 of the previously mentioned 65 pulsars. I also developed a number of post-processing scripts to be able to efficiently sift and inspect the raw single-pulse search output our search pipeline. Because of the large amount of sky covered by LPPS, roughly 70% of the northern sky, we used the survey to derive a limit on the amount of bright dispersed bursts in the low-frequency radio regime (in the absence of strong scattering). The LPPS survey was performed in such an early stage of LOFAR’s commissioning that a number of data quality issues presented themselves. In particular, LOFAR was not yet properly calibrated. To present the aforementioned rate limit in terms of flux, rather than signal-to-noise ratio, I was therefore compelled to derive an estimate of the sensitivity reached during the LPPS survey. LPPS’s results are presented in Chapter 3.

The second commissioning survey, the LOFAR Tied-Array Survey (LOTAS), used a mode of LOFAR that trades field-of-view for more sensitivity. LOTAS was thus biased towards large instantaneous sensitivity as opposed to the LPPS survey which was biased towards large amount of sky coverage and long integration times. Because of the decreased field-of-view of a single observation in LOTAS, constraints on observing time and limits to the processing capacity, we did not attempt to survey the full Northern sky. Instead we observed a strip $\sim 10$ deg off of the Galactic plane. This avoids excessive scattering while still observing relatively close to the Galactic plane where most pulsars are present. For this survey I updated the search pipeline developed for LPPS to also deal with LOTAS data, and participated in the testing of this new pipeline. I inspected the periodicity search results and performed all the single-pulse search processing. LOTAS resulted in the re-detection of 27 previously known pulsars.
CHAPTER 1. INTRODUCTION

of which 4 were independent discoveries (again sources also recently found with the GBT). Furthermore, we report the first two new pulsar discoveries using LOFAR, thus proving that a sparse digital aperture array is well suited to performing pulsar surveys. We provide timing solutions for these two pulsars, one of which I derived. The results of the LOTAS survey are presented in Chapter 4. Together the two pilot pulsar surveys will be submitted as one article of which I am the lead author.

For the two LOFAR commissioning pulsar surveys we performed both frequency domain and time domain searches. The former are sensitive to periodic emission while the latter are sensitive to single pulses. Single pulses can be detected from bright and/or nearby pulsars. While the first pulsar, B1919+21, was discovered through its single pulses, most successful surveys in the following decades used frequency domain searches as those are more sensitive to weak pulsars. After the discovery of a new class of neutron stars with highly intermittent pulses, the RRATs, single-pulse searches again became a standard part of pulsar survey data reduction. In Chapter 5 I describe a set of scripts that I developed to extend the standard single-pulse search facilities in the PRESTO data reduction package. During the data processing it became clear that the standard PRESTO single-pulse search plots can be impractical in the presence of bright pulsar or RFI signals. I therefore created a new more condensed visualization for these data sets. Furthermore we describe a script that can help extract pulsar signals from data pre-processed with PRESTO. We also treat some of the limitations that the script currently has and how those can be overcome.

The final science chapter of this thesis reports on targeted searches of a famous, possibly radio quiet, X-ray/γ-ray pulsar called Geminga. We performed a 4-hr beam-formed observation of Geminga using the full LOFAR core at high time resolution. Because the precise rotational ephemeris of Geminga is known from Fermi Space Telescope γ-ray observations we did not have to perform a full blind search of the radio data to determine whether Geminga is visible at low radio frequencies; only a search in dispersion measure space was required. I am the lead author of this chapter, I searched the data for single dispersed radio pulses and compared the sensitivity of our observation to those reached for the earlier claimed detections. These very sensitive observations did not detect Geminga, despite earlier claims that it is visible a low radio frequencies.