PROCEEDINGS OF SCIENCE

Preface

Carole Jackson
ASTRON
Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
E-mail: jackson@astron.nl

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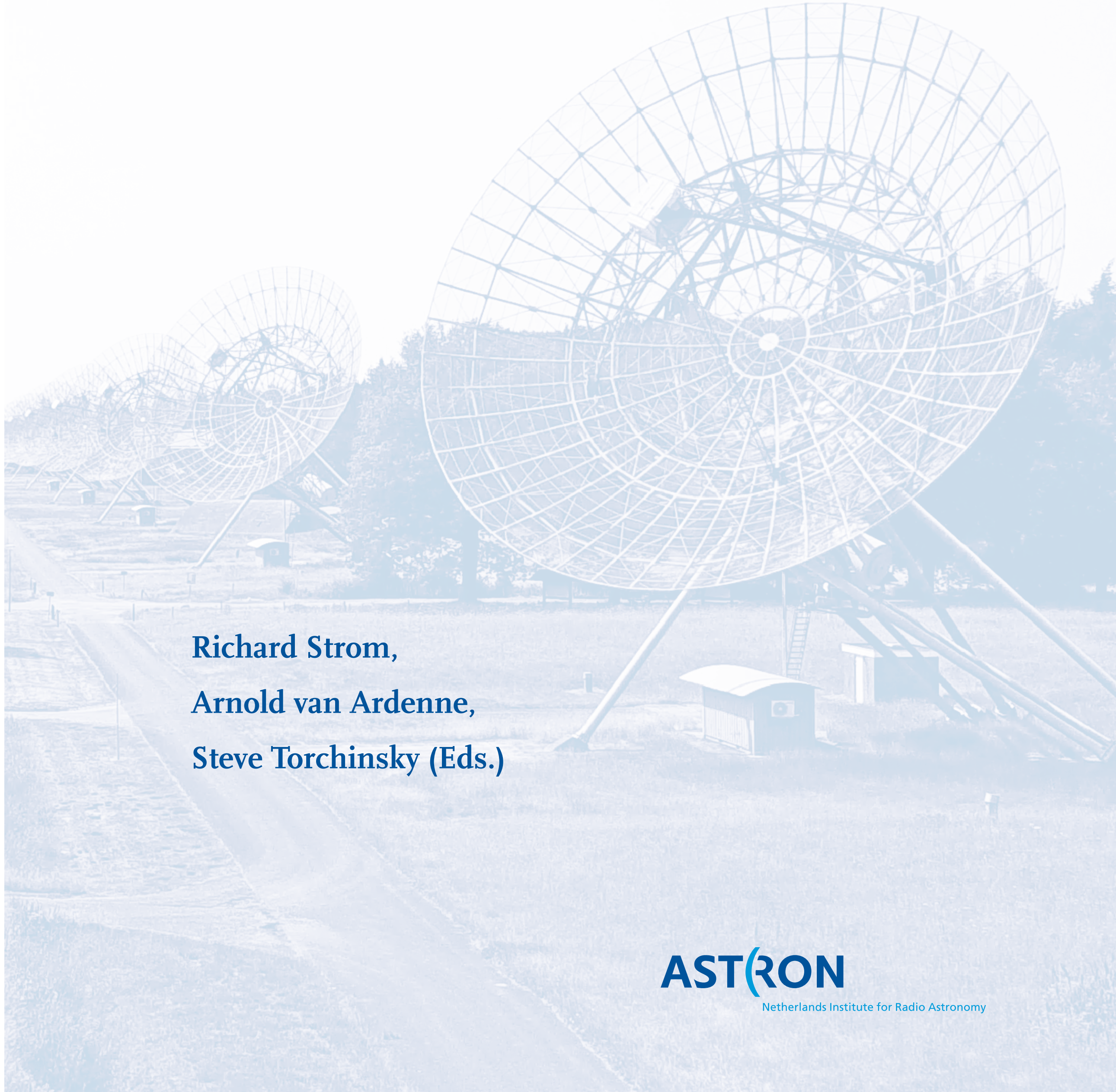
50 Years Westerbork Radio Observatory, A Continuing Journey to Discoveries and Innovations
Richard Strom, Arnold van Ardenne, Steve Torchinsky (eds)

50 YEARS WESTERBORK RADIO OBSERVATORY,
A CONTINUING JOURNEY TO DISCOVERIES AND INNOVATIONS

Dedicated to the Memory of Ger de Bruyn

50 years Westerbork Radio Observatory

A Continuing Journey to Discoveries and Innovations



Richard Strom,

Arnold van Ardenne,

Steve Torchinsky (Eds.)

ASTRON
Netherlands Institute for Radio Astronomy

COLOPHON

Editors:
Arnold van Ardenne
Richard Strom
Steve Torchinsky*)

Advice:
Frank Nuijens

Photography:
Harm-Jan Stiepel

Design:
Jan Hulzebosch**)

Production coordinator:
Truus van den Brink-Havinga

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ASTRON is the Netherlands Institute for Radio Astronomy. We observe and investigate the signals that the Universe emits at radio wavelengths. Our mission is to make discoveries in radio astronomy happen. ASTRON is an institute of the Netherlands Organisation for Scientific Research (NWO).

*) Astroparticle Physics and Cosmology, Observatoire de Paris, CNRS/IN2P3, Université Paris-Diderot, CEA
**) Drukkerij Van Gorcum, Raalte

Preface

In September 2018 we celebrate fifty years since the completion of the Westerbork Synthesis Radio Telescope (WSRT). In 1968 it hailed a new era of astronomy, joining the One-Mile Telescope located at Cambridge UK, exploring the new technique of dish-based interferometry. Over its lifetime, WSRT has been used for a wide range of high-resolution centimetre wave radio astronomy, from studying our solar system to probing galaxies at the edge of the Universe.

A clear theme emerges from this retrospective. The continuing success of this instrument relies on the extensive teamwork of scientists and engineers. Right from the start, this team delivered the WSRT with a clear vision to provide the Netherlands, and the wider international astronomical community, with a telescope of exceptional dynamic range and stability of operations. Throughout its 50-year lifetime, the WSRT has continually evolved, driven by this ongoing engineering-science interlink, testing and maturing novel concepts to deliver world-class capabilities. Moreover, the longevity of the WSRT as a system, underpinned by the collaborative esprit de corps, demonstrates not only the instrument's performance, but also the high level of expertise passed on through generations of astronomers and engineers.

This collection of papers on the WSRT's history, discoveries, current and future promise provides a fitting tribute to the ambitious engineers and scientists of the 1960's who brought this array to the Dutch and international landscape.

WSRT can lay claim to its place in the history of the advancement of scientific knowledge. Teams of Dutch and international astronomers have made remarkable breakthroughs in science, stretching the capabilities of this telescope. A few highlights include the detection and confirmation of dark matter in spiral and dwarf galaxies, the millisecond pulsar in the constellation Vulpecula, the discovery of giant and double-double morphology radio galaxies, and the first map of the radiation belts of Jupiter together with the Pioneer flyby of 1973. Many significant discoveries of WSRT are described in detail throughout this book.

Looking back

From today's viewpoint, we can conclude that fifty years has been a long time in terms of astronomy development: Contemporary telescopes benefit from the massive developments in electronic technologies compared to those of the era when the WSRT was conceived. The WSRT infrastructure, i.e. the dish array itself, stands as a solid and enduring foundation, proving highly adaptable to new innovations through its lifetime.

Given the cost of a new telescope in 2018 can far exceed any one country's budget, it is insightful to review how the WSRT came to exist: After the completion of the Dwingeloo 25m single dish radio telescope in 1956, astronomers in the Netherlands, and neighbours Belgium and Luxembourg, looked towards the next step. The Benelux Cross Antenna Project was a proposal to build a pair of parabolic cylinders. Unfortunately, this project did not come to fruition, but it was the catalyst for what came soon afterwards. With the emergence of a new technique for radio astronomy, and the energy of a remarkable Dutch leader, the astronomer Jan Oort, the ambition for the WSRT was born.

In the late 1950s, aperture Synthesis imaging was developed by the group led by Martin Ryle at Cambridge University. The establishment of this significant technique, since adapted for medical and other devices, culminated in Martin Ryle and Tony Hewish receiving the Nobel Prize (1974). The Cambridge group designed and built the 'One-Mile' telescope array at Mullard Radio Astronomy Observatory near Cambridge, using the newly available 'powerful' computers able to deal with the computationally intensive Fourier transform inversions necessary for aperture synthesis.

It was Professor Oort (Leiden University) who drove the effort to build the WSRT, realizing the potential of radio interferometry. Oort's primary scientific driver was to study cosmology through studies of extragalactic radio galaxies, a topic that had become particularly divisive with the 'static universe' interpretations of the earliest, shallow radio source surveys. From the outset, the design for the WSRT was for twelve 25 m telescopes on an east-west baseline, extending over 1.5 km. Construction began in 1966/67. The first telescope was in place by August 1967, and the twelfth before the end of 1968. As detailed in this volume, and in the 25-year anniversary volume* the WSRT was significantly upgraded between 1975-1980 with the addition of two movable dishes, extending the array to baselines up to 2.7 km. In the early 1980s, new digital back end systems utilizing the major leaps in processing technologies greatly increased the processed data rates, allowing astronomers to observe increasingly wider bandwidths and at finer resolution.

As a National Facility, the WSRT is a common-user instrument, and like the majority of such astronomical facilities, it is made available to the whole community on a free-to-use basis. This has ensured fair access to the very best science proposals. WSRT data remains the property of the science team for 18 months to allow for analysis and publication. After this period, it is considered public and is freely shared for others to use in their research.

* *The Westerbork Observatory, Continuing Adventure in Radio Astronomy, Eds E. Raimond, R. Genee, Astroph.&Space Sc. Library, Vol 207, 1996,Kluwer ISBN0-2973-4150-3*

WSRT today and future

After its major upgrade in 2000, the WSRT contributed to key HI science and surveys, one of a small number of major radio interferometers operating in the cm-wavelength regime, e.g. the Karl G Jansky Very Large Array (VLA), One Mile (UK) and the Australia Telescope Compact Array (ATCA). The WSRT has one feature that sets it apart from most other radio telescopes with equatorial mounted dishes, whereas most other telescopes have an alt-azimuth mount design. The equatorial mount requires steering (movement) on only one axis to track an object on the sky. Compared to alt-azimuth designs, the WSRT's receivers remain stationary with respect to the sky during an observation - this is particularly powerful when dealing with polarisation observations, and moreover allows the relatively simple implementation of a receiver in the aperture plane, i.e. an *aperture plane phased array*.

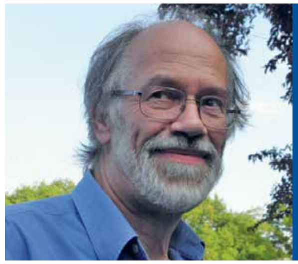
The emergence of the global collaboration to realize the Square Kilometre Array (SKA) in the early 2000's drove novel technology research. Whilst ASTRON commenced the development of phased array feeds/receivers (PAFs) as a potential technology for SKA, it became clear that this would also be an upgrade path for the WSRT. In this way the WSRT provided a vibrant platform with which to explore enabling technologies and industrial partnerships towards the future, including LOFAR and SKA. Thus, in 2015, twelve of WSRT's dishes were removed from operations whilst the PAF-based system upgrades are installed. The other two dishes remained productive operating within the European VLBI Network (EVN) and doing other research (e.g. for Galileo calibration), utilizing the Multi-Frequency Front End system (MFFE, 120 MHz to 8.3 GHz).

Today ASTRON is in the final phase of commissioning this PAF-based system, termed the APERture Tile In Focus, as described in more detail in this volume. Now named "Apertif", this system encompasses a 4-year upgrade that completely re-equips the backend and processing systems of the WSRT. WSRT-Apertif will be one of only two arrays in the world with the phased array feed systems (PAF). The other, ASKAP (the Australian SKA pathfinder), will be the southern hemisphere 'sister' telescope. It is notable that the WSRT has the largest raw collecting area, a factor that may well prove invaluable for the calibration of these complex systems. Notably the design of the two PAF systems (WSRT and ASKAP) are similar in concept but differ in implementation such that these will inform the community as we look to future upgrades. This future may include the adoption of PAFs for SKA as it matures in the next decade beyond its initial build design ("SKA phase 1").

With Apertif, WSRT stands ready to map the medium-deep view of the Universe in hydrogen at 21 cm, providing legacy surveys for researchers of the future. This Apertif system also offers a powerful way to monitor the transient sky, opening up the systematic detection of extreme-power and rare events.

In terms of field-of-view and sensitivity, the compatibility of WSRT with ASTRON's LOw Frequency Aperture Array's (LOFAR), gives the astronomical community a unique pair of instruments to explore the northern sky. ASTRON together with its partners will ensure these deliver the science to establish the important legacy surveys for the 2020's. WSRT together with ASKAP will map the sky providing the primary solution (called the *sky model*) to be used for SKA. In conclusion I would like to thank the authors and editors for their contributions to this anniversary volume. On behalf of the entire community, I acknowledge the support from the Netherlands Organisation for Scientific Research (NWO) of ASTRON, the WSRT and the user community over the last fifty years of exploration and discovery, and look to many more years to come.

Carole Jackson
General & Scientific Director
ASTRON 2018



A.G. (Ger) de Bruyn,

13 July 1948 – 9 July 2017

The idea of putting together this book on the accomplishments of the WSRT since it was put into operation in late 1969 was enthusiastically embraced by Ger de Bruyn a few years ago. Having been part of at least 40 years of WSRT operation, development and science, he had a good overview of whom to ask to contribute and on what topics to focus for a book that would in a factual, educational and entertaining way convey the story of engineers and scientists working together to make and keep the WSRT the successful instrument it has been since it conception. It is therefore extra sad that Ger died so suddenly in 2017 and was not able to see the making of this book through to the end. The editors and contributors would therefore like to dedicate this book not only to almost 50 years of WSRT operation, development and science, but also to Ger's career in radio astronomy which has been so closely tied to the WSRT for the last four decades.

Ger studied astronomy at the University of Leiden and received his doctorate in 1976 on a thesis entitled "Radio investigations of active spiral and Seyfert galaxies" under the supervision of Prof. Harry van der Laan. His thesis research was based on early radio continuum observations with the WSRT. Before joining the scientific staff at ASTRON (the Netherlands Institute for Radio Astronomy) in 1978, he spent two years at the Carnegie Institute/Hale Observatory in Pasadena as a Carnegie Fellow, where he used the Hale Observatory facilities to obtain optical spectra of many active galaxies of the kind he studied for his thesis.

Back in the Netherlands, he devoted most of his attention to using the WSRT at its limits to address a broad range of scientific questions. This was possible due to his excellent and ever-increasing understanding of synthesis imaging, including all the subtle effects of the earth's troposphere and ionosphere, the telescopes, the receivers, the backend and the correlator. Ger's drive to get the most out of the telescope made him famous amongst his peers, and for several decades Ger and his technical colleagues at ASTRON continually pushed the telescope to its limits by coupling forefront scientific research to creative and clever methods for processing the data. This led to the introduction of the so-called redundancy calibration, making use of the regular layout of the antennas of the WSRT. The redundancy calibration has made it possible to reach record dynamic-range radio images with this telescope.

Over the years the frequency coverage of the WSRT was expanded to both higher and lower frequencies, and Ger and his colleagues and students made enormous progress, especially at the lowest frequencies. An attempt to find signs of very distant neutral-hydrogen objects led to the discovery of very complex polarized emission from the galaxy. Follow-up research has shown that this complexity is pervasive in our Galaxy. To study these structures in detail, Ger and his colleagues and students introduced a new technique, rotation measure synthesis, which brings out these complex structures in all their detail and is a powerful tool for its interpretation.
In the late nineties the Westerbork array was used to image the radio emission of the entire northern sky at low frequency (327 MHz), and Ger played a pivotal role in the planning, calibration and analysis of this survey, the Westerbork Northern Sky Survey WENSS. The catalogues and images of this survey are a great asset for the general astronomical community and are widely used.

Some twenty years ago the idea was worked out that it should be possible to measure the extremely weak signal of neutral hydrogen in the early universe once it is heated by the first generation of stars. Ger was intimately involved in this effort. This turned out to be one of the prime motivations to build the Low Frequency Array LOFAR, designed by ASTRON engineers and realized about ten years ago. Ger, his colleagues and students prepared carefully to use LOFAR to detect the neutral-hydrogen signatures in the early universe. Efforts to detect these signatures are well underway through improved understanding of the telescope and the complexity of removing all effects from unassociated radio emission, including the effects of radio interference and the ever-changing ionosphere, which greatly affect the precision of these measurements. While shifting his interest to LOFAR Ger remained connected to the WSRT and continued to participate in discussions about the WSRT's future

Ger will always be remembered as a very creative, stimulating, knowledgeable, but most importantly friendly and generous colleague, focusing all attention on everyone and everything except himself. An important part of his scientific heritage is a large number of students, postdocs and senior researchers who continue to contribute to radio astronomy in the way he used to.

Thijs van der Hulst

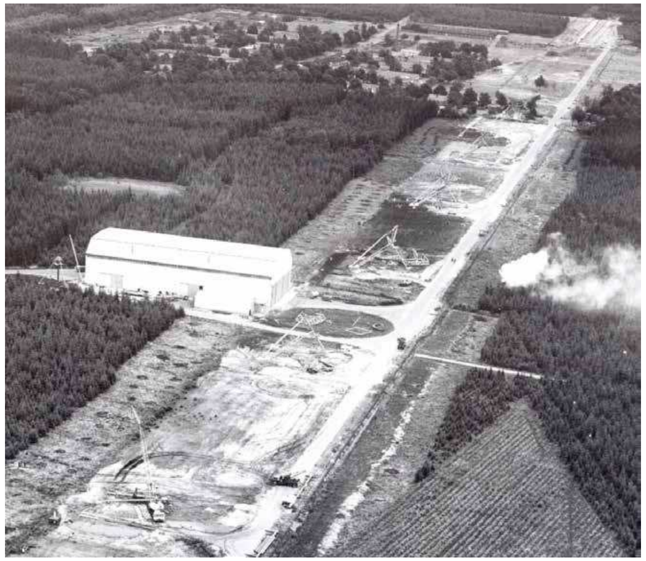
Summary

This book describes a 50-year journey of the Westerbork radio telescopes. The journey is filled with scientific discoveries and new astronomical insights that have provided new knowledge about the Universe. This book is also about the context in which this research was made possible and therefore it is also about the *non-astronomical discoveries* such as the contribution to wireless communication ("WiFi").

Such a journey is only possible in an environment where excellent teams of engineers and scientists are capable of translating state-of-the-art technologies into the instrumental dreams of the astronomers.

In this book, the people involved and witnesses of the journey report their personal experience and views. Of course, many others have made a contribution, and whilst they may not have a mention in this book, it would not have been possible without them. Here we acknowledge the contributions of all the support staff, observers and technicians, many of whom were pioneers working 24/7 shifts.

The book starts with the earliest history of the relatively young branch of astronomy that is now called radio astronomy. The Netherlands commenced organized research from the early 1950s, notably led by giants such as Jan Oort and other visionaries, along with government and business support. The construction of the then world's largest movable 25 metre radio telescope in Dwingeloo, was a turning point as a first instrument dedicated to research. This book is about Jan Oort's next "natural" step, namely the set of 14 (initially 12) 25-metre radio telescopes in Westerbork distributed over a distance of 2.7 km capable of detecting 100 times more detail of radio sources with a much greater sensitivity than the single Dwingeloo dish. The picture (left) from 1966 shows the telescope construction in progress, looking from the west (bottom) to the east in the distance. The assembly hall is clearly visible in the



middle. A special chapter in this book discusses the special design features of the telescopes that, from 1968 on, provided the community with so much good science.

In the first ten years, the telescope was developed to be able to observe 24/7. Part of this development included moving the Leiden-based Laboratory to (now) ASTRON in Dwingeloo, eventually including the entire computational and support systems. This centralisation at ASTRON significantly shortened the production time for observing results: the quality of the instrument could ultimately be assessed instantaneously and possible improvements could be applied immediately. It was also possible to use the instrument as one large telescope in an international network of other telescopes. This enabled joint and simultaneous observations. This so-called Very Long Baseline Interferometry (VLBI) ultimately resulted in the establishment of the JIVE (Joint Institute for VLBI)-ERIC (European Research Infrastructure Consortium) in Dwingeloo. Also in this phase, the basis was laid for making observations in the time domain, in combination with the "traditional" imaging technique for which the telescope was originally built.

After the first ten years of fantastic discoveries, including detecting giant radio sources that are many times larger than the full moon, a phase of greater competition with other international telescopes followed. In particular with the American Very Large Array, now known as Karl G. Jansky VLA – named after the first discoverer of radio waves from the Universe in 1933. The picture below shows the Westerbork Synthesis Radio Telescope, named after the underlying observation technique, in the early nineties in full operation. In the upper right corner the two distant telescopes can still be seen.

As a result of constant investments by the Netherlands towards state-of-the-art telescope instrumentation, signal and data processing techniques and training (including international exchange and cooperation with, among others, universities and industry), a solid foundation was laid for modern world-class radio astronomy.

By making use of special properties of the telescope, such as the fact that the distance between the telescopes could be very accurately recorded, great successes followed. This feature and the huge stability of the instrument led to sky images of unsurpassed accuracy and "depth". The latter relates to the possibility of being able to observe very strong radio sources simultaneously with sources that are more than a million times weaker, in the same "radio" image. This feature improved our calibration techniques and progressed hand-in-hand with a deep understanding of the underlying mathematical-physical generic instrumental description. Without this and further developments, LOFAR and the international SKA project would not have been possible in a meaningful way. This also applies to Apertif, the new Westerbork observing system that was "invented" in the Netherlands. Using the accumulated knowledge and skills

and the use of intense computer and data processing techniques, the whole system works as a "radio" camera to instantaneously observe a much larger field of view.

This book will take you on a journey that shows how all this became possible. En route important side roads have been taken, leading to broad social applications. I invite you to come along on this journey, to wonder about the destinations and to enjoy the anecdotes along the way that are naturally part of this type of endeavor.

On behalf of the editors,
Arnold van Ardenne

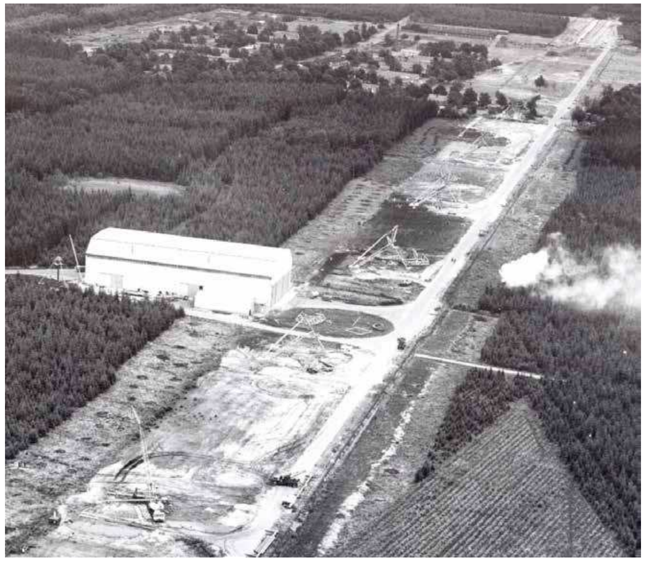
Samenvatting

Dit boek beschrijft een reis van 50 jaar met de Westerbork radiotelescopen. De reis is gevuld met wetenschappelijke ontdekkingen en nieuwe sterrenkundige inzichten die steeds weer nieuwe onderzoeken over het heelal mogelijk hebben gemaakt. Het gaat ook over de context waarin dit mogelijk werd gemaakt en daardoor ook over bijzondere niet-sterrenkundige ontdekkingen zoals de bijdrage aan draadloze communicatie ("WiFi").

Zo'n reis is alleen mogelijk in een omgeving waarin excellente wetenschappers samenwerken met top-ingenieurs die de laatste stand van de techniek kunnen vertalen in de instrumentele dromen van de sterrenkundigen.

In dit boek zijn betrokkenen en getuigen van die reis aan het woord die vanuit hun persoonlijke beleving en kijk op zaken verslag doen. Natuurlijk hebben ook vele anderen een bijdrage geleverd. Zij konden weliswaar geen plaats in dit boek krijgen maar zonder hen zou dit verslag niet mogelijk zijn geweest. Te denken valt aan de ondersteunende staf, de waarnemers die als echte pioniers in het prille begin 24/7 diensten moesten draaien, de vele technici etc.

Het boek begint met de vroegste geschiedenis van de relatief jonge tak van sterrenkunde die nu radiosterrenkunde wordt genoemd. Nederland begon daarmee middels georganiseerd onderzoek vanaf begin jaren '50, vooral door grootheden als Jan Oort en andere visionairs waaronder overheid en bedrijfsleven. Na de bouw van de toen grootste beweegbare 25 meter radiotelescoop ter wereld in Dwingeloo, kwam een instrument beschikbaar waarmee het onderzoeksgebied écht op gang kwam. Dit boek gaat over Jan Oort's volgende "natuurlijke" stap, namelijk de rij van 14 (aanvankelijk 12) 25meter radiotelescopen in Westerbork over een afstand van 2,7 km die 100 keer meer detail van radiobronnen kan waarnemen met daarbij een veel grotere gevoeligheid. Het plaatje hiernaast uit 1966 toont de vroege stand van de constructie fase van de telescopen kijkend vanuit het westen (beneden) naar het oosten in de verte. In het midden is



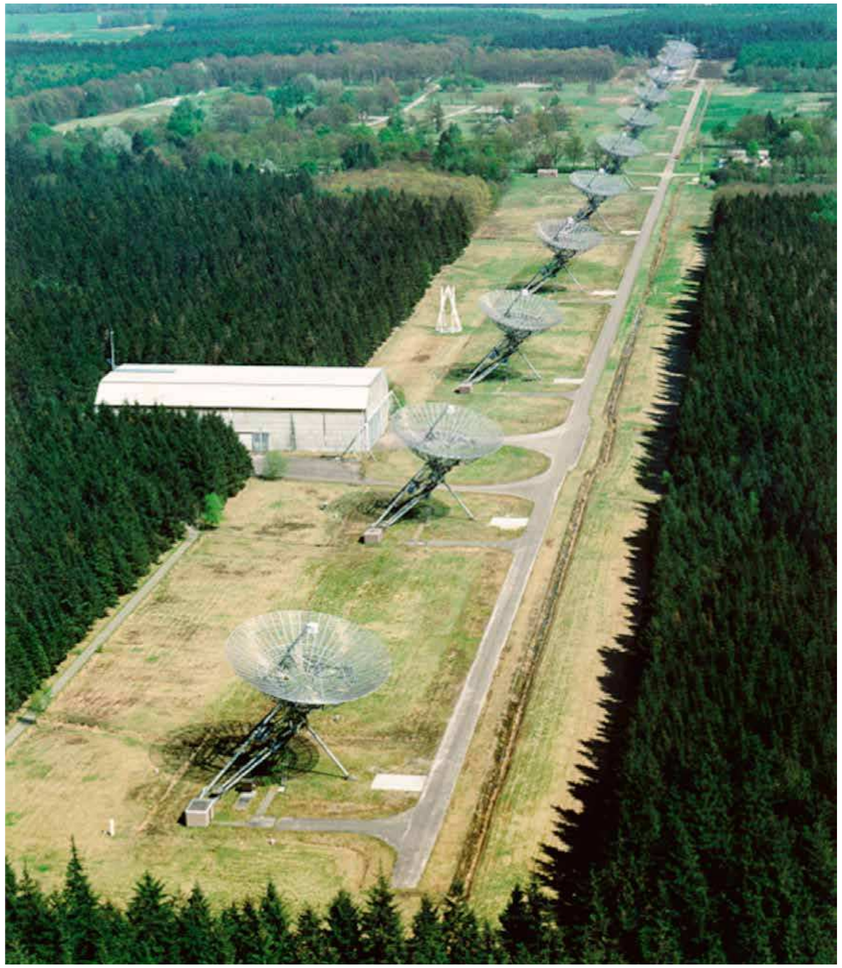
duidelijk de assemblagehal zichtbaar. Er is een speciaal hoofdstuk in het boek opgenomen dat ingaat op de bijzondere constructie van de telescopen die vanaf 1968 de gemeenschap zoveel goede wetenschap heeft opgeleverd.

In de eerste tien jaar werd de telescoop uitgebouwd tot een compleet waarneeminstrument dat 24/7 waarnemingen kon doen. Daartoe werd het Laboratorium van Leiden naar (nu) ASTRON in Dwingeloo verplaatst en uiteindelijk werd ook het hele rekenintensieve proces van het maken van de hemelafbeeldingen overgeplaatst. Door deze verkorte cyclus kon de kwaliteit van het instrument uiteindelijk instantaan worden beoordeeld en eventuele verbeteringen direct worden aangebracht. Ook werd het mogelijk om het instrument als geheel in te zetten als één grote telescoop in een internationaal netwerk van andere telescopen. Zodoende konden gezamenlijk en tegelijkertijd waarnemingen worden gedaan. Deze zogenaamde Very Long Baseline Interferometry (VLBI) heeft uiteindelijk uitgemond in de vestiging van de JIVE (Joint Institute for VLBI)-ERIC(European Research Infrastructure Consortium) in Dwingeloo. In deze fase werd ook de grondslag gelegd voor het doen van waarnemingen in het tijddomein e.e.a. in combinatie met de "traditionele" beeldvorming techniek waarvoor de telescoop aanvankelijk was gebouwd.

Na de eerste tien jaar van fantastische ontdekkingen zoals reuze-radiobronnen die vele malen groter zijn dan de volle maan, volgde een fase van grotere concurrentie met andere internationale telescopen. Met name met de Amerikaanse Very Large Array, nu de Karl G. Jansky VLA genoemd - naar de eerste ontdekker van radiostraling uit het heelal in 1933. Het plaatje hieronder toont de Westerbork Synthese Radio Telescoop, zogenoemd naar de onderliggende waarneemtechniek, begin jaren negentig in vol bedrijf. In de rechterbovenhoek zijn nog vaag de twee verre telescopen zijn te zien. De gehele "basislijn" is daarmee 2,7km geworden.

Door in Nederland voortdurend te investeren in state-of-the-art telescoop instrumentatie, signaal- en data-verwerkingstechnieken en opleiding (waaronder internationale uitwisseling en samenwerking met onder meer universiteiten en bedrijfsleven), kon een stevige grondslag worden gelegd voor de moderne radiosterrenkunde van wereldfaam.

Door gebruik te maken van bijzondere eigenschappen van de telescoop, zoals het feit dat de afstand tussen de telescopen heel precies was vastgelegd en meerdere malen voorkomt, kwamen grote successen voort. Deze eigenschap en de enorme stabiliteit van het instrument, leidde tot hemelafbeeldingen van extreme nauwkeurigheid en "diepte". Dat laatste heeft betrekking op de mogelijkheid heel sterke radiobronnen te kunnen waarnemen tegelijkertijd met bronnen die meer dan een miljoen keer zwakker zijn, in hetzelfde "radio"-beeld. Deze verbeterde calibratie-techniek ging hand in hand met een diep begrip van de onderliggende wiskundig-fysische generieke instrumentele beschrijving. Zonder deze en verdere ontwikkelingen zouden LOFAR en het



internationale SKA-project niet zinvol mogelijk zijn geweest. Dat geldt ook voor Apertif, het nieuwe Westerbork waarneemsysteem dat in Nederland werd "uitgevonden". Met gebruikmaking van de opgebouwde kennis en kunde en de inzet van intense computer- en data-verwerkingstechnieken werkt het geheel als een "radio"camera die een veel groter beeldveld kan waarnemen.

Dit boek neemt u mee op een reis die laat zien hoe dit alles mogelijk werd en waarbij en-passant ook belangrijke zijwegen werden bewandeld leidend tot brede maatschappelijke toepasingen. Ik nodig u van harte uit op deze reis mee te gaan en u te verwonderen over de reisdoelen en om te genieten van de anekdotes onderweg die natuurlijk altijd met dit soort grootse inspanningen gepaard gaan.

Namens de redactie,
Arnold van Ardenne

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