Engineering Capstone Design of a Radio Telescope

Dr. Stephen Andrew Wilkerson P.E., York College of Pennsylvania

Stephen Wilkerson (swilkerson@ycp.edu) received his PhD from Johns Hopkins University in 1990 in Mechanical Engineering. His Thesis and initial work was on underwater explosion bubble dynamics and ship and submarine whipping. After graduation he took a position with the US Army where he has been ever since. For the first decade with the Army he worked on notable programs to include the M829A1 and A2 that were first of a kind composite saboted munition. His travels have taken him to Los Alamos where he worked on modeling the transient dynamic attributes of Kinetic Energy munitions during initial launch. Afterwards he was selected for the exchange scientist program and spent a summer working for DASA Aerospace in Wedel, Germany 1993. His initial research also made a major contribution to the M1A1 barrel reshape initiative that began in 1995. Shortly afterwards he was selected for a 1 year appointment to the United States Military Academy West Point where he taught Mathematics. Following these accomplishments he worked on the SADARM fire and forget projectile that was finally used in the second gulf war. Since that time, circa 2002, his studies have focused on unmanned systems both air and ground. His team deployed a bomb finding robot named the LynchBot to Iraq late in 2004 and then again in 2006 deployed about a dozen more improved LynchBots to Iraq. His team also assisted in the deployment of 84 TACMAV systems in 2005. Around that time he volunteered as a science advisor and worked at the Rapid Equipping Force during the summer of 2005 where he was exposed to a number of unmanned systems technologies. His initial group composed of about 6 S&T grew to nearly 30 between 2003 and 2010 as he transitioned from a Branch head to an acting Division Chief. In 2010-2012 he again was selected to teach Mathematics at the United States Military Academy West Point. Upon returning to ARL's Vehicle Technology Directorate from West Point he has continued his research on unmanned systems under ARL's Campaign for Maneuver as the Associate Director of Special Programs. Throughout his career he has continued to teach at a variety of colleges and universities. For the last 4 years he has been a part time instructor and collaborator with researchers at the University of Maryland Baltimore County (http://me.umbc.edu/directory/). He is currently an Assistant Professor at York College PA.

Dr. Stephen Andrew Gadsden, University of Guelph

Andrew completed his Bachelors in Mechanical Engineering and Management (Business) at McMaster University in 2006. In 2011, he completed his Ph.D. in Mechanical Engineering at McMaster in the area of estimation theory with applications to mechatronics and aerospace systems. Andrew worked as a post-doctoral researcher at the Centre for Mechatronics and Hybrid Technology (Hamilton, Ontario, Canada). He also worked as a Project Manager in the pharmaceutical industry (Apotex Inc.) for about three years. Before joining the University of Guelph in 2016, he was an Assistant Professor in the Department of Mechanical Engineering at the University of Maryland, Baltimore County. Andrew worked with a number of colleagues in NASA, the US Army Research Laboratory (ARL), US Department of Agriculture (USDA), National Institute of Standards and Technology (NIST), and the Maryland Department of the Environment (MDE). He is an elected Fellow of ASME, is a Senior Member of IEEE, and is a Professional Engineer of Ontario. Andrew is an Associate Editor for the International Journal of Robotics and Automation and is a reviewer for a number of ASME and IEEE journals and international conferences. Andrew earned the 2019/2020 University Research Excellence Award for the College of Engineering and Physical Sciences based on his research activities at the University of Guelph. He is also a 2019 SPIE Rising Researcher award winner based on his work in intelligent estimation theory, and a 2018 Ontario Early Researcher award (ERA) winner based on his work in intelligent condition monitoring strategies. He was also awarded the 2019 University of Guelph Faculty Association (UGFA) Distinguished Professor Award for Excellence in Teaching in the College of Engineering and Physical Sciences.

Dr. Kala Meah, York College of Pennsylvania

Kala Meah received the B.Sc. degree from Bangladesh University of Engineering and Technology in 1998, the M.Sc. degree from South Dakota State University in 2003, and the Ph.D. degree from the

University of Wyoming in 2007, all in Electrical Engineering. From 1998 to 2000, he worked for several power companies in Bangladesh. Currently, Dr. Meah is an Associate Professor in the Electrical and Computer Engineering program, Department of Engineering and Computer Science, York College of Pennsylvania, York, PA, USA. His research interest includes electrical power, HVDC transmission, renewable energy applications, energy conversion, and engineering education.

Prof. Donald Jerome Hake II, Kinsley School of Engineering, Science, and Technology - York College of Pennsylvania

2020 York College of Pennsylvania Mechanical Engineering Capstone Design of a Radio Telescope

Stephen Wilkerson, Kala Meah and Don Hake, of York College, PA
and Andrew Gadsden, University of Guelph, ON N1G 2W1, Canada

This paper presents an engineering capstone design project that is community or service-based. By and large, most students in the school's capstone program design and build a car for competition in the Baja or Formula collegiate program. However, there are several other growing options that students are exploring. In 2019-20, one of the options was for students to design and build a star tracking mechanism for a 4.5-meter radio telescope. This paper presents the ongoing telescope work and, where appropriate, contrasts that with the traditional capstone projects like Baja. In particular, a series 8345 Prime focus radio telescope is to be modified to track stars. This means that we could use the 8345-dish, but little else. Nearly every component of the telescope system had to be reengineered and constructed. The instrument collection device will be modified to scan the sky using the hydrogen line. The telescope is to be placed at the John C. Rudy Park, in York County Pennsylvania and operated by the York Astronomical Society (YAS). The mount was to include both azimuth and elevation tracking with remote control from a website. The park service was to handle the details surrounding the foundation, fencing, control room, and power; however, the college ended up providing these features as well. This paper details the design and construction of the telescope's mechanical components by the students. This Project Based Learning (PBL) course allows the students to manage the design process with minimal input from the instructors. How we did this should be of interest to others wanting to try the same techniques. While there is considerable structure to the program, students are encouraged to manage and run the program based on what they have learned in the past three to four years at the college. Nonetheless, some faculty assistance was required for this program and we discuss the benefits and drawbacks of these interactions. Additionally, the course's design helps promote Self-Regulated Learning (SRL) and Life-Long Learning (L^3) of the students. The academic advisors overseeing the work served more in a mentoring role than as project managers. Not surprisingly, this project had numerous financial and engineering constraints to include the difficulties surrounding a 1-ton telescope and rotating mechanisms being operated in a public park atop a 9-foot pole. These constraints necessitated both student and faculty grant applications. Furthermore, the paper details the design and solution to some of the more difficult manufacturing limitations of the college's facilities. Finally, the paper discusses the educational value of this project's approach along with the social and environmental issues that needed to be overcome.

Introduction:

Traditional capstone design projects at the college have been aligned with collegiate competition. More recently, students have become interested in service-based capstone design projects. This paper details some of the accomplishments and difficulties with designing and building a radio telescope for the York Astronomical Society. Students at the college choose between Baja and Formula car competitions and service-based design and build problems such as *"Shadowfax"*[1], drone projects, medical devices and radio telescope design. More often than not, students receive their choice of capstone projects. Like the college's engineering *Co-op*[2] program, this senior course is considered critical in our student's development. Figure 1 shows the Series 8345 Prime-Focus Telescope which was our starting point for this project. The customer's requirements for this telescope was that it be able to track star systems and be remotely controlled.

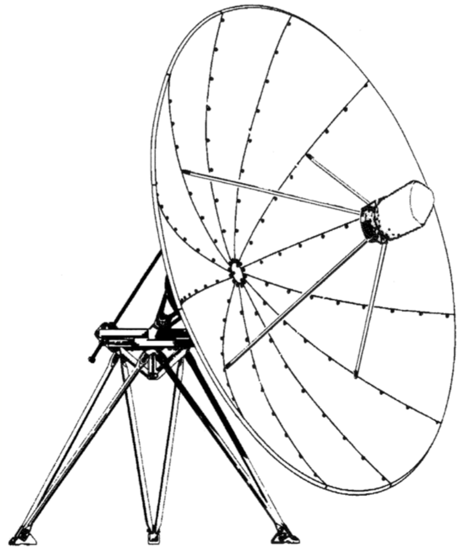

Figure 1. The Series 8345 Prime-Focus Main Antenna

The faculty underestimated the complexity and scope of the project and thought this could be accomplished within a year. This turned out not to be the case for this capstone. This year-long course begins in the summer semester, usually the research and design portion of the project, and finishes in the spring semester during the build and test portion of the project. A fall *Co-op* semester separates the two semesters. Typical capstone design projects require that the students research their project, plan and design an appropriate solution, and then in the spring semester build and refine the design solution. During the first semester, the students present their research to one another with potential solutions to problems. Faculty act as moderators attempting to keep the students on track, and within some reasonable budget. The big question for this project was whether to use an equatorial[3] or altitude azimuth[4] design for the telescope's rotation. The equatorial is a far simpler design for tracking the stars as it only needs to rotate about one axis once it is set up. However, the mechanical issues were far more difficult, and an altitude azimuth arrangement was chosen.

Fortunately for this project, the students continued to work on the design issues through the fall semester while they were doing their last *Co-op* experience at a local company. Therefore, they had a viable design with most of the big issues addressed by the end of the fall semester. The problems that remained had to do with manufacturing. The college shop is not set up to do large objects and the mechanism weighed more than a ton fully assembled. Even the sub-components weighed hundreds of pounds which led to a number of logistic and safety issues. Another issue was that this device was to be placed in a public park and professional

---

[1] Shadowfax is a private corporation, non-profit human services agency that supports individuals with disabilities: https://shadowfax.org/

[2] *Co-op* refers to the college engineering program's 3 semesters of work study for companies in the area that each engineering student must complete to graduate.

[3] Equatorial mounted telescopes: https://en.wikipedia.org/wiki/Equatorial_mount

[4] Altitude azimuth designs: https://en.wikipedia.org/wiki/Altazimuth_mount

engineers, machinist, welders needed to be employed to complete and approve the proposed design. These activities required far more funding than originally envisioned.

Nonetheless, this course is considered critical to our student development and another course cannot be substituted to replace it. Not surprisingly, the course helps our engineering program fulfill many of our ABET requirements. This course is well suited for Self-Regulated Learning (SRL). Cassidy [1] points out that SRL is becoming increasingly relevant and valuable in higher education and equally important to a student's self-evaluation. Goldberg et. al. [2] discusses the level of student-centered learning and the role of the student in their own education. We also use a model similar to the Goldberg model where the instructor takes the role of a facilitator for the student's learning. These techniques require collaborative, cooperative, problem/project-based learning. Dunlap et. al. [3] further points out how PBL is an "apprenticeship for real-life problem solving" and this approach sets up the student for success in their future engineering careers. The goal of the course can be stated from these seven fundamental outcome objectives:

(1) an ability to solve complex engineering problems;
(2) an ability to engineer design solutions that meet specified needs;
(3) an ability to communicate effectively to a variety of audiences;
(4) an ability to recognize ethical and professional responsibilities and make sound judgments;
(5) an ability to function on a team, establish goals, plan tasks, and meet objectives;
(6) an ability to develop and conduct experimentation to evaluate their own project; and,
(7) an ability to research solutions to problems as needed.

Many of these goals form a template to help students learn and evaluate their own progress. In general, students like structure but it is equally important to allow them the opportunity to both succeed and fail. Instructors act more as facilitators and evaluators then architects of the projects. Students set their own goals and milestones while instructors provide feedback and some guidance where needed. However, each student must:

(1) keep an engineering notebook for weekly assessment;
(2) attend weekly project meetings;
(3) provide evidence of completion of various design, construction, testing, and system integration milestones throughout the semester;
(4) participate in and develop content for presentations and poster sessions;
(5) submit a summative technical report describing their individual capstone project contributions; and,
(6) maintain professionalism at all times when interacting with team members or faculty members.

The grading process for the capstone design is evaluated in several criteria shown in Table 1.

Weekly Notebook Entries	10%
Weekly Progress Reviews/Demos	15%
Milestone Presentations & Demos	20%
Summative Technical Report	20%
Capstone Expo Poster	5%

Effectiveness in Engineering Team and Professionalism	30%
Peer Review: Multiplier	

Table 1. Capstone grading rubric

At the beginning of the project, it was desired that the telescope be redesigned to track stars and then be reassembled at the John Rudy Park in York County by the end of the spring semester; finishing a single class capstone design. As we approach the end of Capstone 2, the project still requires significant work. On the face of this, it would seem that this was a failure; however, this is not the case. The capstone design has done more to achieve the goals as stated above than any other capstone that I have been involved with during the last 25 years. Student and faculty members greatly benefited from this learning experience. One highlight of the program was that the first year's capstone team gave a paper at the SARA conference and made significant progress despite not finishing the whole project. Before providing a summary of our observations from this PBL capstone, a brief overview of the design and build progress by the students is provided.

Design:

This particular radio telescope had been a high school project, years earlier, and the device had been sitting in storage for approximately 15 years. The radio telescope was obtained by York Astronomical Society from the high school student's original project. The details of the original project are contained within two papers presented at the 2019 SARA conference in Green Bank, West Virginia [5,6]. The original telescope could be moved in elevation but was fixed at its base with limited rotation capabilities. The original radio antenna was designed for a wide range of applications but was particularly well-suited for CATV operations receiving video from domestic satellites at several different frequencies. It was the desire of the Astronomical Society to use the antenna to gather data in the 1420MHz range also known as the hydrogen line. Additional information on the basics of radio astronomy and why 1420Mhz was selected are available in the "Introduction to Radio Astronomy" presentation at the 2016 UAT workshop, Green Bank by Greg Hallenbeck [7]. Additional information on radio Astronomy can also be found in the literature [8-14].

Considerable attention was given to potential alternative designs. The constraints placed on the students also included job cost, so not all possibilities could be entertained for this project. In the normal engineering process for a design, trade-offs, costs, ease of use, and maintenance must be included. Decision matrices were formed and the students as a group weighed the positives and negatives to arrive at a final design. In the process of developing a solution to this project, a series of designs evolved in a spiral development of the final design that is now being built. The crux of the difficulties in this project is to design and build a radio telescope that will survive the elements (wind and cold), be easy and inexpensive to maintain, as well as be structurally sound. The objective is to have a telescope that will last over 30 years into the future. This project is far beyond the capabilities of a typical mechanical engineer student from a 4-year institution; however, it provides significant learning opportunities.

The final structure can be broken into four major components: the dish, elevation and azimuth rotating parts, counter balance, and the stand. Figure 2 shows a blow-out of these major components. The existing 8345 Prime-Focus radio disk was already built and required only minimal modifications. In fact, the only modification envisioned was to improve the mount from the counter balance to the main hub of the disk. Therefore, the three remaining parts are: the *Post*, the *Azimuth and Elevation Mechanisms*, and the *Counter Balance*. The parts of this telescope are large, heavy and the steel thicknesses are substantial. These components also turned out to be well-beyond the manufacturing capabilities of York College's machine shop and personnel. Knowing this meant that much of the project needed to be made elsewhere. The details of these components are contained in [3,4]

Figure 2. Major Components of the Assembly

Progress:

First year capstone students spent the whole summer deciding which design made the most sense. Decisions like whether to use an equatorial mount or altitude azimuth design and what type of actuation to use were among the decisions. An initial design was proposed. While the students were away on *Co-op* in the fall they continued to work on the project. This was a decision they have to make on their own. There is no academic requirement that they do any work on the capstone project during the fall and most students do not advance their capstone projects during this period.


Figure 3. Telescope Altitude azimuth

However, these students chose to continue working on the project and by early spring they had the altitude azimuth mechanism mostly built. Figure 3 shows the mechanism with a temporary wooden elevation frame and small dish. Using this the students were able to move the mechanism and do some initial testing. This was the starting point of the Capstone 2 team. Most of the components in this mechanism were well beyond the capabilities of our shop to manufacture. Some of the steel was in excess of 1.5 inches thick to support the 1000-pound telescope that would sit atop it. The contrast between the first-year capstone students and the second could not have been greater. More on this in the outcome section.

Second year students began their capstone by checking the calculations and ordering steel to make the remaining elements of the telescope mount. There was a multitude of things remaining to be done. One key element was to get the post built and installed at the park. In order to do this, the students needed to complete the following tasks:

- Build post components and have them welded and painted.
- Get permits and parks permission to install pole.
- Have a professional engineer review and approve the plans.
- Install a temporary fence.
- Dig foundation hole.
- Install reinforcement rebar and anchor bolts, foundation was 10’x10’x3’ deep requiring 35 thousand pounds of concrete.
- Run conduit for wiring back to control shack.
- Figure 4 shows some of the progress during the fall semester.


Figure 4a. Foundation


Figure 4b. Rebar Reinforced


Figure 4c. Concrete Pad

Figure 4. John Rudy Park Site for Future Radio Telescope

Work continued into the winter months and Figure 5 shows the status of the current site. The mounting pole has been installed with a permanent parameter fence. There is also a specialized lightning protection system at the base of the post. Major items that remain include: assembly of altitude azimuth mechanism, testing, painting of dish and parts, building of counterbalance, and cover for the unit.

Figure 5. Post Assembly at John Rudy Park

At the time of the presentation of this work, the telescope should be fully tested on the test stand and ready to be installed in the park. The test stand is shown in Figure 6a.

Figure 6a. Test Stand and Control Unit

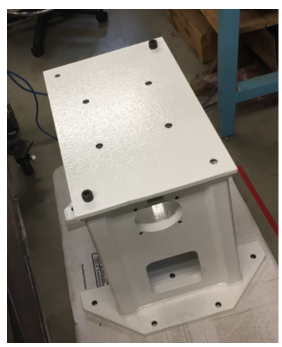

Figure 6b. Elevation Mount

Figure 6c. Painted Dish Parts (Required Special Paint)

Figure 6. Remaining Part of the Telescope

While many of the components are now nearing final assembly, there is little chance this project will be completed by semester-end requiring yet another capstone team to complete the remaining tasks. What we have learned from the process will benefit future students but is important to review here.

Student Outcomes:

This paper focuses primarily on the mechanical engineering students' contributions as the computer engineers, computer science, and electrical engineering work is not yet nearing completion. The other teams consisted of about three times as many students as the mechanical engineering portion. These student outcomes will be reported in subsequent publications.

The first-year students consisted of three highly motivated individuals who were passionate about the project and its outcome. There was already some expertise in the area of building complex structures and this certainly helped the process. All three seniors working on the project the first year were very capable and made significant contributions and sacrifices. In the second year, we enlarged the mechanical engineering effort with five students working on the project. In hind-sight, we should have had seven to 10 students both years. As stated in the introduction, we had seven desired outcomes for each of the students. The rubric below shows the ranking for each student in the study for the two years thus far. Each student was given a ranking on a 1-10 scale assessing their observed performance in each area.

	Student	C1	C2	C3	C4	C5	C6	C7	M
Year 1	a	10	10	9.5	10	8	10	10	10
	b	9	9	9	9	9	9	9.5	10
	c	9	9	9	9	9	9	9.5	10
Year 2	d	8.5	9	8	9	8	9	9	10
	e	8	8	8	9	8	8	9	9.5
	f	8	8	7	9	8	8	9	9
	g	8	8	8	9	8	7	9	8
	h	8.5	8	8	9	8	8	9	8

(c1) an ability to solve complex engineering problems.
(c2) an ability to engineer and design solutions that meet specified needs.
(c3) an ability to communicate effectively to a variety of audiences.
(c4) an ability to recognize ethical and professional responsibilities and make sound judgments.
(c5) an ability to function on a team, establish goals, plan tasks, and meet objectives.
(c6) an ability to develop and conduct experimentation to evaluate their own project.
(c7) an ability to research solutions to problems as needed.
(M) Motivation

First year students worked the entire year and continued to make contributions to the project while working full time at their *Co-op* site in the fall semester. They wrote and presented a paper at a professional symposium detailing their efforts. In the second year, only one student worked during the fall *Co-op* semester with the other students contributing sporadically. In the first year, two of the students were committed and interested in astronomy while in the second year only one student showed more than a passing interest in the projects purpose. All of the students in both years were good engineering students, but not all of the students were passionate about astronomy. Students understood what needed to be done, they were able to organize the project in a meaningful way and they knew when something was beyond their capabilities. In other words, they knew when to seek out additional expertise and advice. For example, the permits to place the telescope at the park required a professional engineer. The foundation also required a professional engineer to design and certify. One student, with the assistance of two others, completely designed the mechanisms and provided a road map for the others to follow from that point on. Their final report was a *"how to"* manual for converting a stationary radio telescope to one that could track the stars. Moreover, this was the paper that was presented at the SARA conference in Green Bank, WVA. Directly after the presentation, students and faculty were approached and offered a grant to help with the process without any solicitation. What is important to note is that each year these projects get an assortment of students. All of the students are capable. Some are more willing to put forth extra efforts than the others. What is required for a successful project is for the instructor to help steer students to where they can contribute at their highest level. In this role, the instructor is also learning how best to motivate and help the students succeed in what will be their most memorable experience of their engineering education. Like the students on this project, the instructors are also learning and adapting to their own SRL experience.

Students who become fully engaged in a project can overcome most learning difficulties and achieve their goals. We have seen this in the PBL project on numerous occasions. The value of self-motivation cannot be understated. If a student is passionate about a project, they will invest whatever time it requires to achieve the required goal. Moreover, SRL can also be observed as students will find the technology they require for their goals and learn it. They will seek out expertise when and where needed. We were constantly amazed with the attention to detail and thought that went into this particular project. So, the question might be asked what makes one student more motivated than another? Certainly, an interest in the topic is a start, but it is far more than that. Most students are also concerned with how they are viewed by their peers. The peer review can be brutal for any student thinking they are going to do the minimum. Failure of this one course guarantees another year at the college. In almost every case where a student does not complete the course, the peer review is the reason for their demise. The capstone design concludes near the end of the semester where the students must present their work to our business partners. The college has more than 60 industry partners and each sends representatives to our review on the last week of the semester. Students typically speak of their work with great pride and accomplishment where they are eager to tell others what they did. If for no other reason, this one event highlights and demonstrates the importance of this PBL course.

Conclusions:

This paper presents a mechanical engineering capstone design project that is community or service-based and uses PBL and SRL to accomplish its goals. For the 2019-20 program, the project was to build a mechanical, star-tracking mechanism, for a 4.5-meter Series 8345 Prime-Focus radio telescope. Students were required to use planning software, Gantt charts, and predictions for completion of the project. Like most engineers, these predictions are overly optimistic. The instructors for this class collect a multitude of data and, before the start of each new class, evaluate the program and its engineering contribution to the students experience at the school. Without exception, capstone design is the most difficult course the students will take and also the most rewarding. Students were able to present their partial results at a symposium. This resulted in a grant to help support the second year's class.

The radio telescope has been modified to scan the sky searching the hydrogen line. The mount included both azimuth and elevation tracking with remote control from a website. At the time of this presentation the unit will have been assembled and partially tested. Barring a catastrophic failure, the telescope should be operational at the park by this time next year. The project will enable students to attend symposiums to present papers and this has shown to be very beneficial for their development. This PBL course allows the students to manage the design process with minimal academic oversight. However, some faculty assistance was required for this program and we discussed the benefits and drawbacks of these interactions. The academic advisors overseeing the work served more in a mentoring role than as project managers. The instructor's role is still evolving and without question these projects get more ambitious every year. I believe we have shown the value of this work for student and faculty development in this paper. The details of the design will be presented in other technical symposiums and will enable other academic institutions to learn and improve upon our student's experience.

References:

[1] Cassidy, Simon. "Self-regulated learning in higher education: Identifying key component processes." *Studies in Higher Education* 36.8 (2011): 989-1000.
[2] Goldberg, Jay R. "Active Learning in Capstone Design Courses [Senior Design]." *IEEE pulse* 3.3 (2012): 54-57.
[3] Dunlap, Joanna C. "Problem-based learning and self-efficacy: How a capstone course prepares students for a profession." *Educational Technology Research and Development* 53.1 (2005): 65-83.
[4] Series 8345 Prime-Focus Manual Antenna Installation Manual, Manual-33N074M, July 2008 Superior Satellite Engineers, Inc.
[5] Smith K, Ullery T, "A 4.5 Meter Radio Telescope for Educational Outreach" Annual SARA conference Green Bank WVA Aug2019.
[6] Shook D., Amtmann W, Berardi A and Wilkerson S, " 2019 York College of Pennsylvania Mechanical Engineering Capstone Design of a Radio Telescope" Annual SARA conference Green Bank WVA Aug 2019.
[7] Marr, Jonathan M., Ronald L. Snell, and Stanley E. Kurtz. *Fundamentals of radio astronomy: observational methods*. CRC Press, 2015.
[8] Roth, Günter D. *Handbook of practical astronomy*. Ed. Günter D. Roth. Springer Berlin Heidelberg, 2009.
[9] Shields, John Potter, and Richard Waxberg. *The amateur radio astronomer's handbook*. Crown Publishers, 1986.
[11] Wohlleben, Rudolf, Hartmut Mattes, and Th Krichbaum. *Interferometry in radioastronomy and radar techniques*. Springer Science & Business Media, 2012.
[12] Tiuri, M. E. "Radio astronomy receivers." *IEEE Transactions on Military Electronics* 8.3 (1964): 264-272.
[13] Hogbom, J. A., and W. N. Brouw. "The synthesis radio telescope at Westerbork. Principles of operation, performance and data reduction." *Astronomy and Astrophysics* 33 (1974): 289.
[14] Thompson, Anthony Richard, James M. Moran, and George Warner Swenson. *Interferometry and synthesis in radio astronomy*. New York et al.: Wiley, 1986.