

Development of a Small Radio Telescope at the Technical University of Cartagena

A duty with our students and society

José Luis Gómez-Tornero*, David Cañete-Rebenaque, Fernando D. Quesada-Pereira and Alejandro Álvarez-Melcón
Dept. of Information and Communication Technologies, Technical University of Cartagena (UPCT), 30202 Cartagena, Spain
email: josel.gomez@upct.es

Abstract—An initiative carried out at the Technical University of Cartagena (UPCT, Spain) to encourage students and promote the interest for Scientific and Engineering Culture between society is presented in this contribution. For this purpose, a medium-term (4 years) project based on the design, fabrication, testing and set-up of a small Radio Telescope system has been carried out. The main novelty is that this project is entirely being done by students of last courses of our Telecommunication Engineering Faculty, under the supervision of four lecturers.

Keywords- *Electrical engineering education; Electromagnetic engineering education; Systems engineering education.*

I. INTRODUCTION

As we are immersed in the “Bologna process” to reach the EES (European Space for Higher Education) [1], academic and government regulators request for innovate experiences to improve the learning process, highlighting the necessity of development of more practical, less theoretical, teamwork, interdisciplinary competencies. Very worrying is the reality detected in the last decade that shows that young people around Europe are losing their interest in Science and Engineering culture (see, for instance the objectives and effort made in Spain by FECYT [2]). Being aware of these facts and feeling responsible as part of a public University, some lecturers of the Telecommunication Engineering Faculty at the Technical University of Cartagena (UPCT) decided to undergo the experience of involving our last course students in the development of a Small Radio Telescope (SRT).

These lecturers coordinate some telecommunications related syllabus like Electromagnetism [3,4], Antenna Engineering [5,6] Microwave Engineering [7-8], or Radio Communication Systems [10]. We thought that Radio Astronomy [11-14], and particularly Amateur Radio Astronomy [15-17] is an interesting application of Microwave Engineering that might motivate students to put effort in these courses [18]. Moreover we thought that involving the students in the setting-up, operation, maintenance and enhancement of a SRT system (see Figs.1-2) could be a good idea to have a permanent practical laboratory where they could feel free to improve their knowledge and skills related with these

technologies. Besides, this Radio Telescope can serve as tool to attract future students to our Faculty, and also very useful to disseminate Radio Astronomy between non-specialized individuals, local amateur astronomers [19,20], and society in general.



Figure 1. Students and lecturers at work mounting the SRT antenna

The main novelty of this activity is that the entire Radio Telescope system (see scheme in Fig.2) is being entirely developed, manufactured, tested and set-up by the students, using the facilities available in our modest laboratories. To our knowledge, this is the first proposal in Spain to promote Radio Astronomy with these particular characteristics. Other public Spanish Universities proposals, such as the ones from the University of Valencia [21] or the University of Cantabria [22] have also made use of a SRT to introduce their students of Physics and Astronomy to this fascinating world. However, in these cases, the entire SRT was designed, manufactured and sold by external Engineering companies [23-26]. Another well-known example is the Spanish-NASA project known as PARTNeR [27] started in 2004, and which involves the use of the 34m diameter NASA Radio Telescope at Robledo de Chavela (Madrid, Spain) to disseminate Radio Astronomy among high-school and University students [28]. Like other Spanish professional Astronomy institutions such as IAA [29] or IAC [30], these initiatives make use of professional and large Radio Telescopes with the aim to make public their facilities and divulgate Radio Astronomy to society. On the contrary, the initiative proposed and carried out at the UPCT

This work has been partially supported by Regional Séneca Foundation under project 02972/PI/05 during 2006-2008, and partially by the Technical University of Cartagena (UPCT) during 2009 and 2010.

has an academic origin, with the main objective to stimulate the potential and improve the learning process of our graduate and postgraduate students in the fields of Electromagnetism, Antenna and Microwave Engineering, and Signal Processing. In the international picture, similar university projects can be found at MIT Haystack Observatory (Boston, MA) [31], Cardiff University (UK) [32], or Saint Mary's University (Canada) [33]. Nevertheless, a secondary objective and interesting consequence is the application of this project to share this amateur SRT between high-school students, local Astronomy associations and society in general, trying to attract new students to our faculties and improve the interest of young people for Science and Engineering. A similar task in an international level can be attributed to the SETI (Search for Extra Terrestrial Intelligence) team [34], in his aim to let individuals collaborate in this search, with projects as the SETI@home [35] or the development of amateur SRTs for SETI Argus Project [36-37].

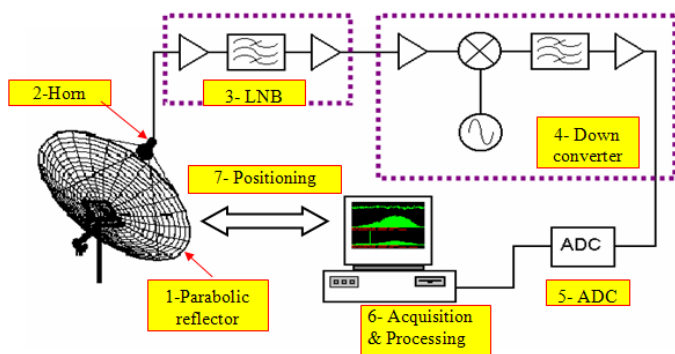


Figure 2. Scheme of the Radio Telescope subsystems

In this paper, the particular objectives of the SRT project undergone at the UPCT will be described, illustrating the methodology used to improve the learning process of the aforementioned undergraduate and postgraduate courses. Also, the response of the students and the results obtained will be addressed, together with the main future lines.

II. OBJECTIVES AND BENEFITS

The main objectives of this initiative, and the associated benefits for the students, can be summarized as follows:

1- **Development of a small radio telescope (SRT)** capable of detecting the **L-band emissions of atomic hydrogen** (1.42 GHz). This frequency was chosen since the hydrogen line emissions from our Galaxy are quite abundant and relatively strong [11]. Moreover, this microwave range provides understanding of high-frequency related phenomena studied in Antenna [5-6] and Microwave [7-10] Engineering without overcoming the 6GHz band, in which the manufacturing and testing of circuits and antennas becomes much more expensive and difficult. Therefore, the microwave receivers working at this frequency are *relatively easier and cheaper to design and manufacture*, if compared with higher frequencies or more sensitive receivers, which might be impractical for modest tools and laboratories like the ones that our graduate students can use.

2- The system (see Fig.2) must be entirely designed, manufactured, tested, set-up and maintained by our students. In this way, the students face a complex project, in which **practical, interdisciplinary, teamwork competences** must be developed with a concrete target. In this way, we try to **make the students realize of their actual developed abilities as future engineers**. It has been found that many students have the feeling of having developed too theoretical, poor practical skills in our Engineer faculties, feeling unprepared for real practical works [1,2]. Even if the lectures do not believe that this feeling corresponds to reality, it is good to make the students realize from an early stage about their actual abilities to face real, practical, complex, interesting engineering projects, so they feel more *motivated and confident*.

3- The SRT system involves different theoretical concepts which the students are supposed to have gained during their graduate and undergraduate courses (mechanics, physics, astronomy, electronics, electromagnetism, microwave circuits, antennas, signal processing, instrumentation...). In this way, we make the students develop **interdisciplinary skills**, gathering the knowledge of all these courses together to face this work. We believe that this is a more realistic and practical position for them to face the real world, opposed to the academic perspective of “unconnected courses” so often addressed by graduate students.

4- Apart from being multidisciplinary, we also look for development of **teamwork competences**, needed for practical big projects which cannot be faced by a single person.

5- Once the initial SRT has been set-up and installed at UPCT, it is intended to be a **constant tool for teaching and upgrading**. The basic system provides an *excellent laboratory* to make *permanent improvements* and *develop future projects* in any of the associate disciplines and technologies. The idea is that the **students of UPCT must feel fry to conceive and propose new project** which might upgrade the performance of the SRT, working out their **creativity and research abilities**.

6- A more *wide objective* is to use this SRT to **attract young people and increase their interest in Sciences and Technology**[1]. Particularly, the SRT is intended to help in the recruitment of new students to our Engineering Faculties [2].

7- Radio Astronomy is not as spread and known in society as its optical counterpart, probably due to the complexity associated to microwave circuits and antennas. The SRT has also the *social objective* of **introducing students and amateur astronomers to Radio Astronomy and linked technologies**.

III. METHODOLOGY

To face objectives 1-5, some UPCT lecturers started by the end of 2004 a set of BsC and MsC final projects, which were supported from 2006 to 2008 by a Regional Foundation project [38]. The methodology was based on the division of the whole SRT system in several subsystems, as illustrated in

Fig.2. In this way, each student could choose the SRT subsystem he or she wanted to work at, either in the initial design or in the continued upgrading. Obviously, the student and the supervisor should be aware of the state of other SRT projects, improving the result of previous projects and responding to the necessities of current works undergone by other colleagues. A total of **4 lecturers and 32 students** got involved from 2005 to 2009 in the development of the different subsystems of the SRT, with an **average extent of 9 months** (one course) per project.

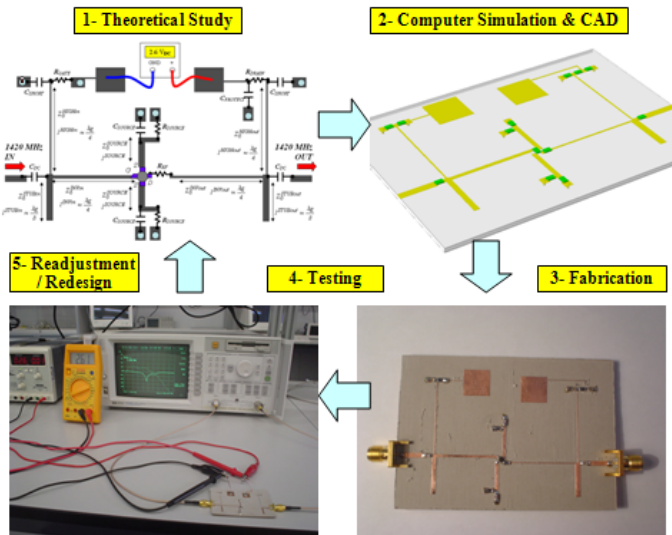


Figure 3. Scheme illustrating the methodology used in each subsystem project for the particular case of the SRT Low Noise Amplifiers (LNAs)

As it is shown in Fig.2, the SRT system is divided in the following comprehensive subsystems:

- 1- Parabolic Reflector
- 2- Horn
- 3- Low Noise Block comprised of:
 - 3.1- RF Band Pass Filters
 - 3.2- Low Noise Amplifiers (LNAs)
- 4- Down Converter comprised of:
 - 3.1- Low Noise Amplifiers (LNAs)
 - 3.2- Local Oscillator (LO)
 - 3.3- Mixer
 - 3.4- Intermediate Frequency (IF) Filters
- 5- Analog to Digital Converter (ADC)
- 6- Acquisition & Signal Processing
- 7- Control of Motors for Positioning and Tracking

It must be noted that each of these subsystems, although connected and dependent on each other, have an individual particular function, which corresponds to a type of hardware signal processing. Moreover, these subsystems practically

cover most of the type of circuits used in analog microwave systems [10], so that the SRT receiver scheme in Fig.2 can be **generalized to many other applications concerning Telecommunication Engineering** and Microwaves for Industrial, Scientific and Medical Applications [7,8]. All the students must have, therefore, a broad perspective of the overall receiver system, and at the same time a more meticulous standpoint of the subsystem they are in charge of. In this way, it is promoted the **interdisciplinary and teamwork competencies**, and a broader knowledge of radio communication systems. The basic methodology of each subsystem project is illustrated in Fig.3, consisting of several steps:

- a) **Theoretical study** of subsystem, using the associated disciplines textbooks [3-10], and particularly one text book developed by the supervising lecturers [39].
- b) **Computer aided design (CAD)** and simulations using commercial software, such as *Ansoft High-Frequency Structure Simulator HFSS* [40] for linear electromagnetic three dimensional simulations, *Agilent Advance Design System ADS* [41] for linear electromagnetic planar circuit simulations, *Applied Wave Research Microwave Office-MWO* [42] for microwave circuit linear and non-linear frequency analysis, and *Orcad PSPICE* [43] for microwave circuit non-linear transient time-domain analysis. Depending on the type of subsystem, the student might have to use one of these packages (or a combination of them), so that the her or she must learn the main differences, similarities and applications of each one of these **commercial microwave CAD tools**.

As descriptive examples, Figs.3, and 4 illustrate the microwave circuit CAD with MWO for the LNAs and the mixers, respectively. Figure 5 shows an example of microwave transient analysis of the microwave local oscillator (LO) using PSPICE. Finally, Fig.6 depicts the electromagnetic CAD of planar microstrip RF filters, while Fig.7 illustrates three dimensional electromagnetic CAD of the horn of the SRT employing HFSS CAD.

- c) **Physical design** of actual prototypes using the more convenient technology. Particularly, planar microstrip PCB (Printed Circuit Board) technology [9] has been used for most of the microwave circuits (LNAs, RF filters, LO, mixers, IF filters), while waveguide technology has been used for some of the RF filters [4] and the horn antenna [6]. In this way, the students have to face different **practical microwave technologies**, understanding their advantages and drawbacks.
- d) **Fabrication of the prototypes** in the corresponding technology using the more appropriate processes, such as photolithography for printed circuits or drilling and mechanization for waveguides and horn antennas. The students gain at this stage a novel **practical perspective about manufacturing processes** (possibilities, limitations,

applications), which usually have not been gained in previous courses.

e) **Testing of the circuits**, using the RF instrumentation available in the laboratories. Again, depending of the particular subsystem and technology, different types of measurements and instruments might be used, such as DC voltage supplies, RF generators, spectrum analyzers, network analyzers, RF probes and oscilloscopes. This part is also very interesting for the students, since they **deal with real instrumentation** which is not used in many theoretical courses.

f) After comparing the results of their experiments with the theoretical design and CAD simulations, it is quite common that the student must make some **readjustments and even redesign the circuits** to improve the performance of the actual designs. In this stage, the students learn the difference between the world of CAD model and the real world, understanding also the **importance of using accurate and efficient electromagnetic/electronic simulation tools**.

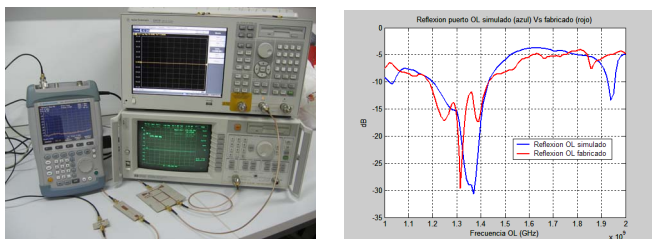
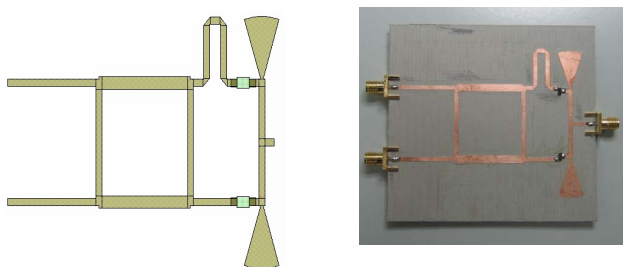


Figure 4. Development of the SRT microstrip mixers

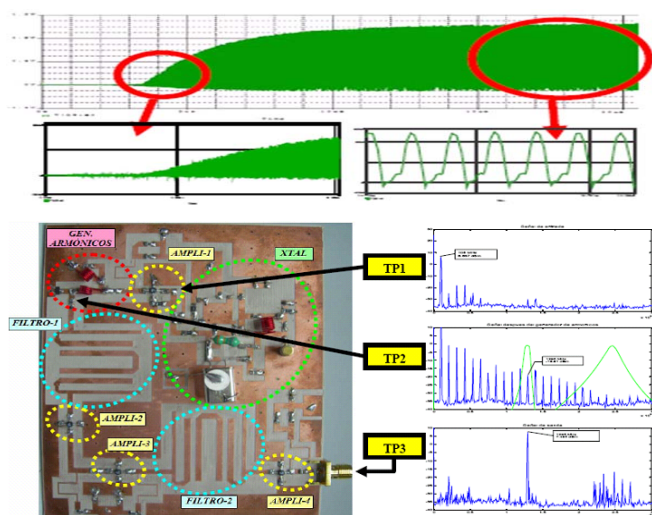


Figure 5. Development of the SRT microwave local oscillator.

Figures 3-9 schematically show some examples of this methodology applied to several of the subsystems of the SRT (LNAs, mixer, local oscillator, RF filters, horn, parabolic reflector and positioning subsystem). Moreover, it must be said that in these four years of work, several improved versions of each subsystem have been designed, so that the students collected the work done in previous years by older colleagues, and worked hard to progress for the better performance of the whole SRT. We believe that this method is very instructive and encouraging for students, since they feel that they are part of a big project in which many people are involved in **teamwork** trying to design the complex system.

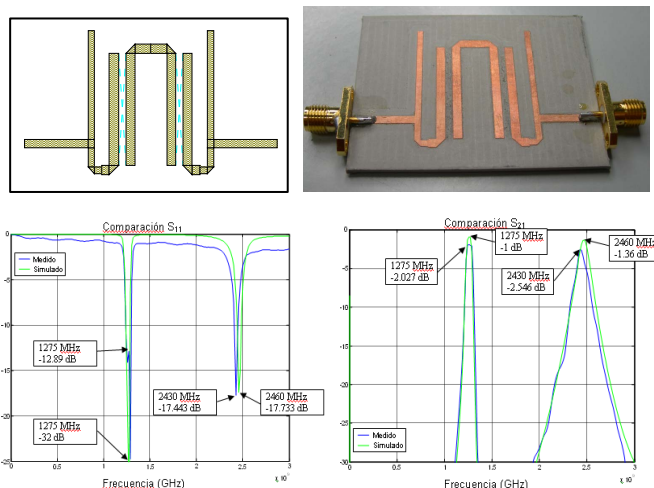


Figure 6. Development of the SRT microstrip band pass filter

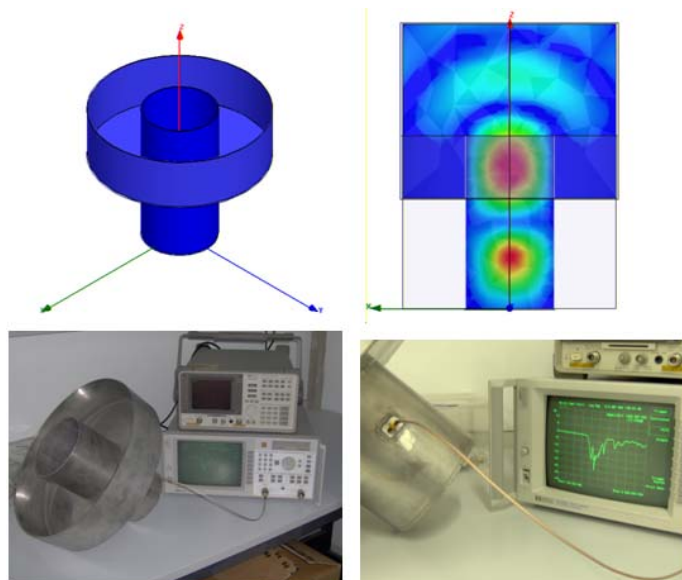


Figure 7. Development of the SRT horn feeding the parabolic reflector

Particularly interesting was the design of the parabolic reflector and the positioning system, shown in Figs.8-9, since they mixed up **interdisciplinary work** involving mechanics and high-power engineering. Another interesting part for the students is the assembly of the different subsystems to conceive the **whole RF receiver** (Fig.2 and Fig.10). For this purpose, especial RF system analysis CAD (*Applied Wave*

Research Visual System Simulator VSS [44]) was used, as illustrated in Fig.10. The same aforementioned methodology is applied for the development of the whole RF receiver, with the particularity that the student must have a deep knowledge of all the RF subsystems involved, which were designed in previous projects. Also, the fabrication and testing of the entire RF receiver is more complicated, since the students must deal with a more complex board and several RF subsystems.

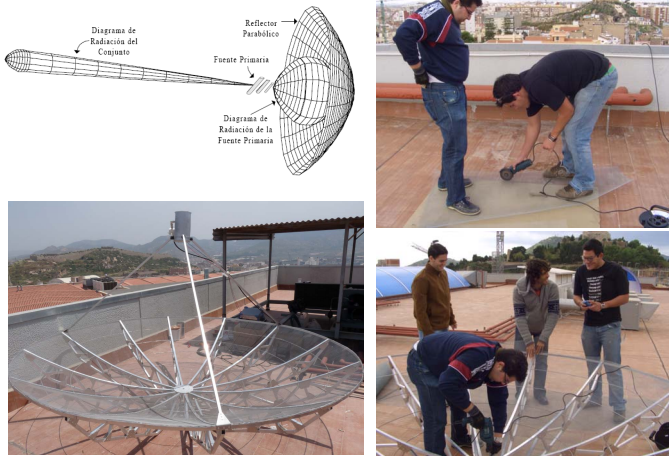


Figure 8 Development of the SRT parabolic reflector

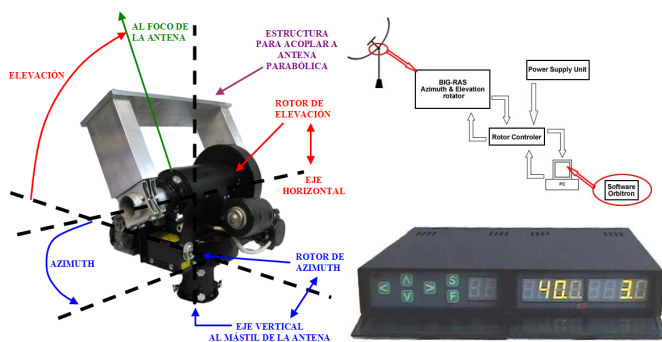


Figure 9. Development of the SRT positioning subsystem

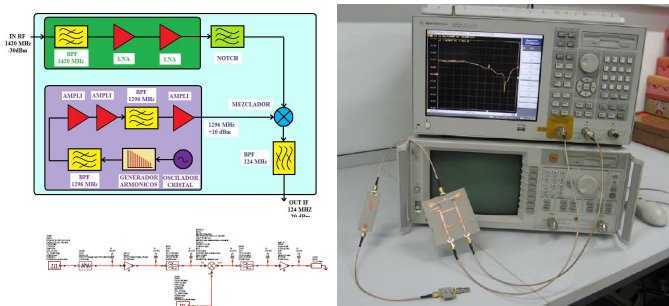


Figure 10. Development and assembly of the whole SRT RF receiver.

The emplacement of the engines and antenna was also very instructive and entertaining for the students, as shown in Fig.11. All participants were very excited to see the SRT located at the final position. For this stage, a solid and stable post was designed, fabricated and sited in the roof of one of the buildings of the University [45]. Finally, the engines were placed on top of the post, and the reflector together with the horn and some LNAs were assembled to it. The students made

careful experiments at this stage, in order to properly place the horn at the focal point of the reflector, as shown in Fig.12. A final picture of the SRT from the outside of the building at UPCT is shown in Fig.13.



Figure 11. Emplacement of the engines and antenna at post.

Finally, a web-page has been created to hold and share updated information of this project [46], including general information about Radio Astronomy and Microwave and Antenna Engineering. Particularly, this web page holds all the technical reports derived from the students' MSc projects, including powerpoint presentations and some interactive applets, which might be useful for other people interested in amateur Radio Astronomy.



Figure 12. Assembly of the horn at the parabolic focal point and tests.



Figure 13. Final emplacement of the SRT at UPCT.

IV. RESULTS AMONG THE STUDENTS

To evaluate the degree of success of this initiative, with respect to some of the objectives described in Section II, several questions were addressed to the students (a total of 32), once they had finalized their project for the SRT. The questions are summarized below:

- 1- Do you think working in this project has made you improve your practical abilities? *(Not at all, Not sure, Sure)*
- 2- Do you think this project has been relevant in your formation as a future Engineer? *(Not at all, Not sure, Sure)*
- 3- Do you think that this project has been relevant to better understand the associated disciplines that you studied in previous courses (microwaves and antennas)? *(Not at all, Not sure, Sure)*
- 4- Do you think that this project has improved your teamwork skills? *(Not at all, Not sure, Sure)*
- 5- Do you think that this project has improved your motivation and interest about the degree you studied? *(Not at all, Not sure, Sure)*
- 6- Do you think that this type of projects could substitute the associated theoretical courses? *(Not at all, Not sure, Sure)*

All the students responded to questions 1-5 with the “*Sure*” answer, showing an **excellent degree of success among the students** with respect to objectives 2-4 of Section II. It is interesting to note that 53% of the students answered “*Not at all*” to the last question, a 31% answered “*Not sure*” and the remaining 16% answered “*Sure*”. Obviously, this project is not intended to replace the theoretical courses, which in opinion of this lecturers are indispensable for the students in order to face the more practical projects proposed in this SRT initiative (as 53% of the students addressed).

From the lecturers’ point of view, it is being a satisfying experience (despite the big effort and time of dedication needed to supervise these projects), since the students showed high degree of interest and satisfaction, presenting own judgement and clever ideas, and yielding fruitful discussions and enhancement. Therefore, we really believe that this initiative strongly improve the learning process of the associated Microwave and Antenna Engineering courses, and it is extensible to any other Engineering course. The main condition is to find a practical and interesting application (in this case Radio Astronomy), making the students face an appealing Engineering task to develop their highest potential.

V. CONCLUSIONS AND FUTURE LINES

Objectives 6-7 of Section II can only be achieved after the SRT is used for **dissemination between high-school students and astronomy amateurs in the future**. Particularly, the first future line is to calibrate the SRT to be able to map our Galaxy, so that appealing results as the hydrogen line map shown in Fig.14 can be obtained and shared with visitors.

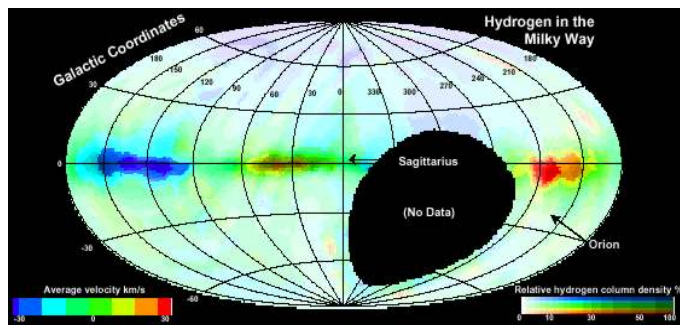


Figure 14. Hydrogen line map of our Galaxy.

Objective 5 is a consequence of the success of the development of the SRT initial system and the good response of the students, so that **this SRT will be used by the students to upgrade its performance and propose new applications**. One of these future upgrades might be the design of an interferometer radio telescope (Fig.15), or the development of receivers and antennas working at other frequencies to detect other interesting signals from our Solar System and Universe. Moreover, the SRT is intended to participate in the SETI project [34,36], which can be another attractive application to increase the interest among the young students and future graduates.

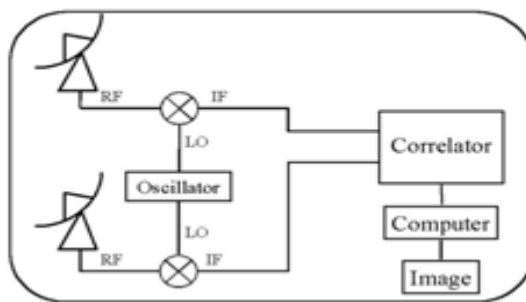


Figure 15. Scheme of a basic linked radio interferometer.

Nevertheless, the authors of this work believe that this type of initiatives are not given enough importance by the actual academic system, which mainly score the lectures by their research results. This fact makes that the endeavor of University lecturers is set on pure research, not being worthy to waste time and energies carrying out dissemination projects like this one which might not be valued in accordance to the effort needed. However, the authors of this paper believe that these enterprises are of key importance to the future of Science and University, and moreover they are a duty with our students and society.

ACKNOWLEDGMENT

This work has been partially supported by Regional Séneca Foundation under project 02972/PI/05 during 2006-2008 [38], and partially by Technical University of Cartagena (UPCT) during 2009 and 2010. This project would have not been

possible without the excellent response and enthusiasm of our students, which are named in chronological order (indicating the course years and the subsystem in which they worked as part of this project): Ricardo Alarcón Llamas (design of LNAs, 2005-2006), Pedro Enrique Ros Avilés (mixer, 2005-2006), Joaquín López Castaño (RF filters, 2005-2006), Mónica Martínez Mendoza (RF filters, 2005-2006), Anna Kamasheva (LNAs, 2006-2007), Gonzalo Peñafiel Beltrán (LNAs, 2006-2007), Mónica Moragón Serano (oscillator, 2006-2007), Adrián Juan Heredia (horn, 2006-2007), Francisco Javier Sandoval Piqueras (mixer, 2006-2007), Ramón Angosto Sánchez (parabolic dish, 2006-2007), Juan Antonio Rosell Franco (RF filters, 2007-2008), Javier Molero Madrid (down converter, 2007-2008), Jesús Mora Rodríguez (parabolic dish and down converter, 2008-2009), Marta Rodríguez García (parabolic dish and down converter, 2008-2009), Cynthia Cerezo (microwave detectors, 2008-2009), Miguel Damián Truque (parabolic dish and positioning system, 2009-2010), Pedro Bermejo (oscillators, 2009-2010) and Javier Jimenez (positioning system and final down converter demonstrator board, 2009-2010). The authors want to acknowledge the support of Dr. Isidro Villó, Dr. Isidro Ibarra and Dr. Rafael Vilar from the UPCT, who made possible the final set-up of the parabolic dish and motors in the buildings of the UPCT, and also the scientific and technical wise advices of Dr. Isidro Villó (UPCT), Dr. José Carlos Guirado Puerta (University of Valencia, Spain), and Dr. José Ignacio González Serrano (University of Cantabria, Spain).

REFERENCES

- [1] <http://www.bologna-bergen2005.no/>
- [2] FECYT: <http://www.fecyt.es>
- [3] R.E. Collin., *Field Theory of Guided Waves*, IEEE Press, 2nd Ed., John Wiley and Sons, 1990.
- [4] S. Ramo, J.R. Whinnery, T. van Duzer, *Fields and Waves in Communication Electronics*, 3rd Edition, John Wiley & Sons, 1994.
- [5] R.C. Johnson, *Antenna Engineering Handbook*, 3rd Ed., Ed. New York, McGraw-Hill, 1993.
- [6] C.A. Balanis, *Antenna Theory, Analysis and Design*, 2nd Ed., John Wiley & Sons, Inc., 1996.
- [7] D.M.Pozar, *Microwave Engineering*, 3rdEd., JohnWiley and Sons, 1998.
- [8] R.E. Collin, *Foundations for Microwave Engineering*, 2nd Ed., IEEE Press, 2001
- [9] I. Bahl, *Microwave Solid State Design*, 2nd Ed,JohnWileyandSons, 2003.
- [10] David M. Pozar, *Microwave and RF wireless systems*, John Wiley & Sons 2000
- [11] J.D. Kraus, *Radio Astronomy*, McGraw-Hill Education, 1966.
- [12] B.F. Burke, Francis Graham-Smith, *An Introduction to Radio Astronomy*, 1994.
- [13] D. Fisher, *Basics of Radio Astronomy*, Jet Propulsion Laboratory, 1997, Document No. JPL D-13835.
- [14] G.L. Verschuur, *The Invisible Universe: The Story of Radio Astronomy*, 2nd Ed, Springer, 2006
- [15] J.M. Lichtman, *Amateur Radio Astronomy, Systems, Procedures and Projects*, 1993.
- [16] Heiserman, *Radio Astronomy for the Amateur*, ISBN 0-8306-5714-2., TAB Books Co., 13311 Monterey Lane, Blue Ridge Summit Pa., 1993.
- [17] W. Lonc, *Radio Astronomy Projects*, ISBN 1889076007, Radio-Sky Publishing, 1996.
- [18] J.E. Salah, P. Pratap, A.E-E. Rogers, "The Educational Role of Small Telescopes in Radio Astronomy" in *The Future of Small Telescopes In The New Millennium. Volume II - The Telescopes We Use*. Terry D. Oswalt, ed.; Astrophysics and Space Science Library, Volume 288, Dordrecht: Kluwer Academic Publishers, p.323-336, 2003.
- [19] County of Murcia Astronomers Agrupation: <http://www.observamurcia.com/>
- [20] County of Cartagena Astronomers Association: http://usuarios.lycos.es/astro_nia_cartagena/
- [21] Valencia University SRT <http://www.uv.es/radioastronomia/>
- [22] Cantabria University STT <http://www.ifca.unican.es/~gserrano/SRT/>
- [23] Radio Astronomy Supplies (RAS) <http://www.radioastronomysupplies.com/>
- [24] Down East Microwave Inc. (DEMI) <http://www.downeastmicrowave.com/>
- [25] CASSICORP <http://www.cassicorp.com/index.html>
- [26] RF Ham Design <http://www.rfhamdesign.com/>
- [27] PARTnER project: <http://laeff.inta.es/partner/>
- [28] O. Suarez, C. Blasco, J.F. Gomez, M. Herranz, B. Montesinos and J. García, "PARTnER, a Radio Astronomy Experience for Students", Teaching and Communicating Astronomy, JENAM'04, EAS Publication Series, 16, 159-165, 2005.
- [29] IAC, Astrophysic Institute of Canary Islands www.iac.es/
- [30] IAA, Astrophysic Institute of Andalucia www.iaa.es/
- [31] MIT Haystack Observatory SRT: <http://www.haystack.mit.edu/undergrad/srt/index.html>
- [32] Cardiff University SRT: <http://www.astro.cf.ac.uk/observatory/radiotelescope/>
- [33] Saint Mary's University: <http://www.ap.stmarys.ca/~lonc/radiotel.html>
- [34] SETI League <http://seti1.setileague.org/>
- [35] SETI @ home: <http://seti1.setileague.org/general/setihome.htm>
- [36] SETI Argus project: <http://seti1.setileague.org/argus/index.html>
- [37] SETI Argus SRT: <http://seti1.setileague.org/hardware/blkdir.htm>
- [38] J.L. Gómez-Tornero. Final Report, "Development of a Small Radio Telescope for Dissemination of Radio Astronomy and Microwave - Antenna Technologies, and Amateur Exploration of out Galaxy", (in Spanish), project granted during years 2006-2008 by Regional Seneca Foundation with code 02972/PI/05., Techn. University of Cartagena, April 2009.
- [39] J.L.Gómez Tornero, Transmisión por Soporte Físico; Ejercicios resueltos de circuitos pasivos y activos de microondas, MORPI, S.L., 2006 (ISBN: 84-95781-70-0).
- [40] Ansoft High-Frequency Structure Simulator (HFSS V.9 0), 2000: www.Anssoft.com
- [41] Agilent Advance Design System ADS 2002, Momentum: <http://eesof.tm.agilent.com/products/ads2002.html>
- [42] Applied Wave Research, Microwave Office (MWO), AWR 2002: http://web.appwave.com/Products/Microwave_Office/Overview.php
- [43] Orcad PSPICE v9.1: <http://www.cadence.com/products/orcad/index.aspx>
- [44] Applied Wave Research, Visual System Simulator (VSS): http://web.appwave.com/Products/Visual_System_Simulator/
- [45] I+D+i builing at UPCT: <http://www.upct.es/idi.htm>
- [46] UPCT SRT web page: <http://www.upct.es/geat>