Karbala International Journal of Modern Science

Manuscript 3306

Improving the BURT’s Sensitivity using Noise Calibration Unit via Crab Nebula Observations

Uday E. Jallod

Lana T. Ali

Hareth S. Mahdi

Kamal M. Abood

Improving the BURT’s Sensitivity using Noise Calibration Unit via Crab Nebula Observations

Abstract

Radio observations from astronomical sources like supernovae became one the most important sources of information about the physical properties of those objects. However, such radio observations are affected by various types of noise such as those from sky, background, receiver, and the system itself. Therefore, it is essential to eliminate or reduce these undesired noise from the signals in order to ensure accurate measurements and analysis of radio observations. One of the most commonly used methods for reducing the noise is to use a noise calibrator. In this study, the 3-m Baghdad University Radio Telescope (BURT) has been used to observe crab nebula with and without using a calibration unit in order to investigate its impact on the signal. Radio observations of crab nebula have been carried out for different periods in 2022. Several parameters of the telescope have been calculated and analyzed using statistical measurements with and without using the noise calibration unit. Those parameters are receiver gain, system temperature, antenna temperature, and degree per flux unit. The results of this research revealed that the fluctuation sensitivity of BURT improved by about an order of magnitude, when the noise calibration unit is used. The root mean square error and the radiometer equation of the antenna temperature decreased to less than 33% and 10%, respectively in comparison to their initial values. In conclusion, the noise calibration unit plays a crucial role to improve the sensitivity of a radio telescope drastically.

Keywords

Crab nebula observation, Radio observation techniques, and Radio spectrometer.

Creative Commons License

RESEARCH PAPER

Improving the BURT's Sensitivity Using Noise Calibration Unit via Crab Nebula Observations

Uday E. Jallod*, Lana T. Ali, Hareth S. Mahdi, Kamal M. Abood

Department of Astronomy and Space, College of Science, University of Baghdad, Baghdad, Iraq

Abstract

Radio observations from astronomical sources like supernovae became one the most important sources of information about the physical properties of those objects. However, such radio observations are affected by various types of noise such as those from sky, background, receiver, and the system itself. Therefore, it is essential to eliminate or reduce these undesired noise from the signals in order to ensure accurate measurements and analysis of radio observations. One of the most commonly used methods for reducing the noise is to use a noise calibrator. In this study, the 3-m Baghdad University Radio Telescope (BURT) has been used to observe crab nebula with and without using a calibration unit in order to investigate its impact on the signal. Radio observations of crab nebula have been carried out for different periods in 2022. Several parameters of the telescope have been calculated and analyzed using statistical measurements with and without using the noise calibration unit. Those parameters are receiver gain, system temperature, antenna temperature, and degree per flux unit. The results of this research revealed that the fluctuation sensitivity of BURT improved by about an order of magnitude, when the noise calibration unit is used. The root mean square error and the radiometer equation of the antenna temperature decreased to less than 33% and 10%, respectively in comparison to their initial values. In conclusion, the noise calibration unit plays a crucial role to improve the sensitivity of a radio telescope drastically.

Keywords: Crab nebula observation, Radio observation techniques, Radio spectrometer

1. Introduction

The crab nebula, the plerion nebula of a type II supernova that exploded in 1054 AD, is one of the most important celestial objects in the history of astronomy. Not only for providing convincing evidence for the existence of pulsars as rapidly rotating neutron stars at the center of core-collapse supernovae. But it also revealed the first-time non-thermal radio emission from a Supernova Remnant, SNR [1]. Several previous studies extensively discussed and explained the mechanism by which this type of electromagnetic radiation is generated [2–4].

In 1950, a plausible theory explaining the radio emission of SNRs was proposed by Alfven and Herlofson [5] and independently by Kiepenheuer [6], which is the synchrotron radiation. According to their hypothesis, a single electron is moving with a velocity that is close to light velocity, and this electron in an external magnetic field will emit a radiation. This radiation is located in the radio region, and the frequency that near this emission reaches its maximum intensity is called the critical frequency for synchrotron emission [7]. A few years later, this hypothesis was confirmed by Mayer et al. by the detection of polarization from the same nebula [8]. Since then, synchrotron radiation has revolutionized knowledge in the field of astronomy, and it has become the fingerprint and the principal tool in identifying and investigating new SNRs and their environments in the radio energy band.

According to Green's classifications and constantly modified review, there are more than 294 firmly classified SNRs in our galaxy about 95% of them have

---

Received 19 February 2023; revised 7 June 2023; accepted 11 June 2023.
Available online 8 August 2023

* Corresponding author.
E-mail addresses: uday.jallod@sc.uobaghdad.edu.iq (U.E. Jallod), lana.t@sc.uobaghdad.edu.iq (L.T. Ali), hareth@uobaghdad.edu.iq (H.S. Mahdi), kamal.abood@sc.uobaghdad.edu.iq (K.M. Abood).

https://doi.org/10.33640/2405-609X.3306

been identified as radio sources [9]. A few more studies were carried out to investigate crab using observations in different bans. For instance, in 2019 a study was carried out and identified crab nebula as a high-energy astrophysical source [10]. In 2020, another study was carried out to demonstrate a turbulent model of the crab nebula's emissions [11]. The estimation of the crab dust mass is achieved via multi spectral observations [12]. Later, several rapid bright flares are observed at high energy along the direction of the crab nebula [13]. The observation at the frequency of 3 GHz using the VLA technique. This technique leads to obtain an image of the entire crab nebula with sub-arcsecond angular resolution [14]. In addition, telescopes, in Canada, France, and Hawaii, were used to map the crab nebula with outer and inner envelopes. This is considered as a wonderful 3D mapping that was achieved by Fourier transform spectrometer [15]. In the last decade, different sizes of radio telescopes were built like (small, medium, and large) radio telescopes that are used to observe different radio sources in our universe [16]. Small radio telescopes are widely used in astronomy, especially at the frequency of 1.42 GHz. This frequency is emitted from neutral hydrogen atoms which are available at any position in the Universe [17]. Therefore, radio observations for such frequency provide us with important information about celestial astronomical objects. There are several types of small radio telescopes, one of the most important of them is a telescope with a diameter of 4.5 m [18]. This telescope is used to map the distribution of neutral hydrogen in the Milky way galaxy [19]. In recent years, other radio telescopes were used to perform solar observations, such as the Medicina and Sardinia radio telescopes. These telescopes have multiple receivers which covers a wide range of frequencies [20]. Although the observations made through radio bands usually suffer from many technical problems related to accurate equipment calibrations over wide frequency ranges. This depends, particularly on the antenna temperature scale and the antenna gain values. In many cases, the calibrations are made by relative comparison of the flux density of the object under study with other sources such as the Sun, the Moon, planets, or any object whose flux density is well defined.

In this paper, the calibration has been carried out via a different technique using the Baghdad University Radio Telescope (BURT) centered at a 21-cm wavelength.

Particularly, a noise calibration unit is connected to BURT and pointed towards crab nebula for the purpose of improving the sensitivity and accuracy of observational data from this interesting astronomical object.

The telescope, in this case, receives the signal from crab nebula as well as from the noise calibration unit itself. Therefore, when the receiver noise is subtracted from the signal received from crab nebula, the results would be more reliable and lead to better understanding of the physical properties of crab nebula.

2. Observation and data reduction

The observations of the crab nebula have been carried out with the 3-m BURT centered at frequency of 1.42 GHz, corresponding to a wavelength of $\lambda = 21$ cm. The bandwidth of the used radio telescope is 0.2 GHz; the system noise temperature ≈ 35 K; and the antenna effective area $A_e = 3.5\ \text{m}^2$ [21].

The optimum values of the BURT spectrometer parameters for observing the source under study were: span of 3 MHz, sweep time of 35s, resolution bandwidth of 100 Hz, and video bandwidth of 10 Hz. The observations were conducted over three months in 2022, from June to August.

Regarding the observations, to ensure the source site is within the main loop of the antenna, the antenna was first directed to the crab nebula position, $\alpha = 5^h34^m94^s, \delta = +22^o00'52.2''$, for about 3 min. Then, in an effort to measure the sky background noise (Fig. 1), the antenna was moved to a position far from the nebula, at least by an azimuthal (ϕ) separation distance of 10° but with the same elevation (θ), to make sure there was no signal coming

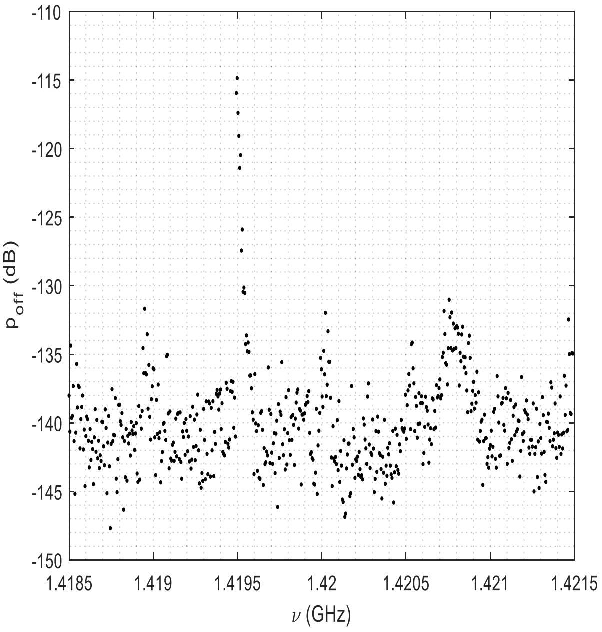

Fig. 1. The measured power from sky background (p_{off}) as a function of frequency.

from the source. This estimation was later subtracted from our data to prevent unwanted signals.

3. Calculations, statistical measurements and results

The calibration of any radio telescope is usually done by specifying several requirements for the noise calibration unit, such as total receiver gain (G_r), system temperature (T_{sys}), and calibration temperature (T_{cal}).

Commonly, these parameters are determined from radio observational data. In this study, to determine the first parameter, G_r has been determined using an On-Off switching technique, aided by a noise calibrator, through the subtraction of the measured initial system noise power (P_{OFF}) from the noise power injected into the BURT receiver (P_{ON}), as shown in Fig. 2. That resulted in a value of $G_r = 30$ dB.

However, the calibration of the second parameter, T_{sys}, requires more parameters along with the observational data. For instance, the spectrum bandwidth frequency Δv and the calibration temperature T_{cal}, that can be obtained from the following formulas [22]:

$$\Delta v = N_{ch} \Delta v_{ch} \tag{1}$$

$$T_{cal} = \frac{P_{ON} - P_{OFF}}{k G_r \Delta v} \tag{2}$$

where N_{ch} is the number of channels, Δv_{ch} is the channel width, and k is Boltzmann's constant.

By setting $N_{ch} = 600, \Delta v_{ch} = 5$ kHz, and using the obtained value of G_r, the resultant calibration temperature was found to be $T_{cal} = 0.3$ K.

p_{on} and p_{off} are the measured power from the source (in our case, the crab nebula, Fig. 3) and blank sky (Fig. 1), respectively, these two powers are used for further estimations as shown in next section.

For the T_{sys} calculations, the noise calibration unit has been used, through two measurements of the power from the blank sky: one with the aid of noise calibration unit (P_{cal}) and the other without (P_{OFF}), and according to the following equation [23].:

$$T_{sys} = \frac{P_{OFF}}{P_{cal} - P_{OFF}} T_{cal} \tag{3}$$

As these parameters became available, many radio terms, such as the antenna temperature (T_A), flux density (S_v), and aperture efficiency (η) can be estimated using the following formulas [24]:

$$T_A = \frac{p_{on} - p_{off}}{G_r k \Delta v} \tag{4}$$

$$S_v = \frac{2kT_A}{\eta A_g} \tag{5}$$

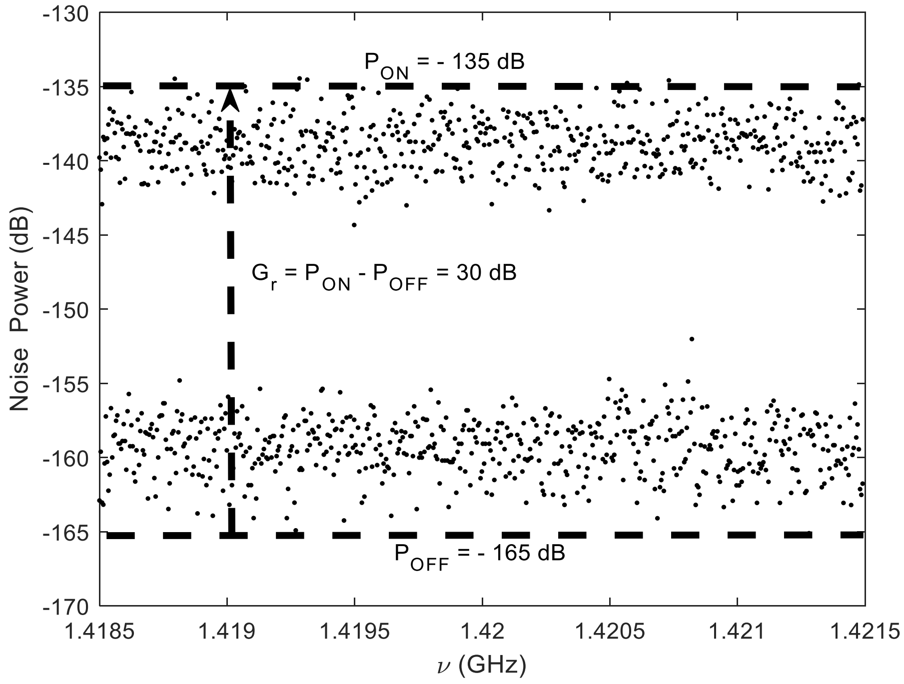

Fig. 2. Noise power from calibration unit as a function of frequency.

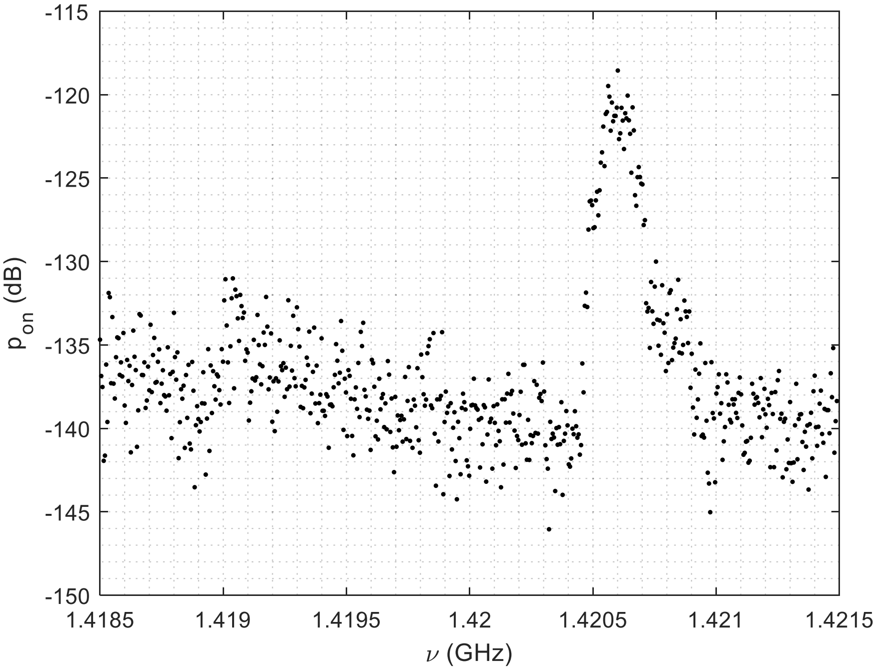

Fig. 3. The measured power from crab nebula (p_{on}) as a function of frequency.

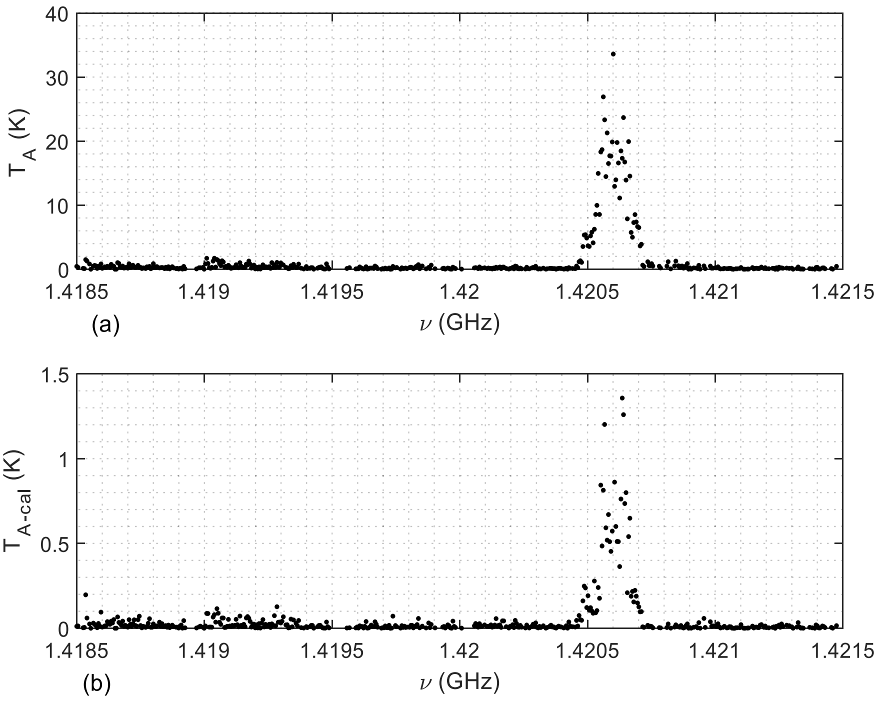

Fig. 4. The obtained (a) un-calibrated and (b) calibrated antenna temperatures from the crab nebula observations as a function of frequency.

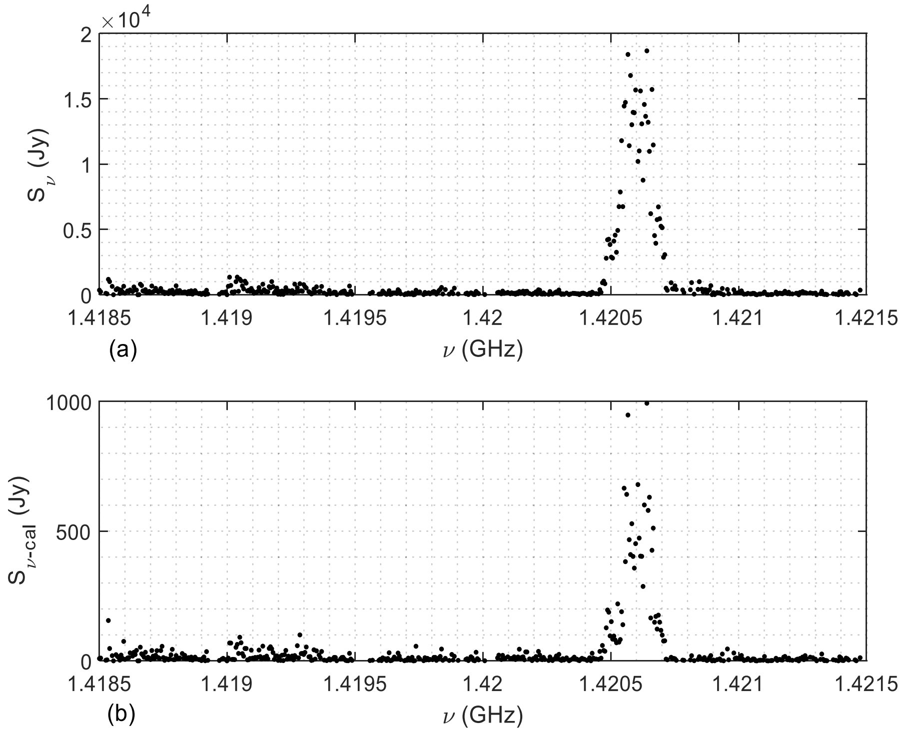

Fig. 5. The (a) un-calibrated and (b) calibrated flux densities from crab nebula observations as a function of frequency.

$$\eta = \frac{A_e}{A_g} \tag{6}$$

where A_e and A_g are the effective and physical areas, respectively.

Hence, by applying Eqs. (3) and (4) on the observational data from crab nebula observations, each of the un-calibrated (T_A) and calibrated ($T_{A-Cal} = \frac{p_{on}-p_{off}}{G_r k \Delta v} T_{sys}$) [25], antenna temperatures, were estimated and demonstrated in Fig. 4.

In addition (Fig. 5-a), shows the resultant flux density of the crab nebula via Eq. (5), along with the calibrated flux density (S_{v-cal}) (Fig. 5-b), which was computed by the following equation [26]:

$$S_{v-cal} = \frac{2kT_{A-cal}}{A_e} \tag{7}$$

Finally, to review our finding, the calibrated degree per flux unit ($DPFU_{cal}$) was determined from the following formula [27]:

$$DPFU_{cal} = \frac{T_{A-cal}}{S_{v-cal}} \tag{8}$$

For verifying the measured radio data with and without noise calibration unit, two statistical measurements were applied. First the root mean square (*rms*), to describe the amount of variance due to random fluctuations of the individual measurements, that it is given by [28]:

$$rms = \sqrt{\frac{\sum_i (x_i - \overline{x})^2}{N}} \tag{9}$$

where x_i is the value of the ith measurement of the antenna temperature, $\overline{x}$ is the average measured value of the antenna temperature, and N is the number of measurements [29]. While the second is the radiometer equation $\sigma(T_A)$, that provides an indication about the fluctuations in the radio telescope measurement as a function of the antenna temperature and the duration Δt and bandwidth Δv over which the observations were made, and it is usually given by [30]:

$$\sigma(T_A) = \frac{T_A}{\sqrt{\Delta t \Delta v}} \tag{10}$$

Δt and Δv are set to be (35 s and 3 MHz).

4. Conclusions

In this study, radio observations of crab nebula have been carried out using BURT in order to investigate the influence of a calibration unit that is connected to the telescope. The calibrated and uncalibrated signals have been compared using statistical measurements. The results of this study showed that the calibration unit improved the signal significantly. The sensitivity of BURT has increased by about a factor of 10. Furthermore, the *rms* decreased from 6 to 0.18, while $\sigma(T_A)$ decreased from 0.003 to 0.0003. These are extremely encouraging findings, because, as the values of T_A and $\sigma(T_A)$ decrease, the sensitivity of detecting a celestial object increases. The results of the calibrated antenna temperature, flux density, and degree flux per unit are found to be 1.4 K, 1000 Jy, and 0.001 K/Jy, respectively. Hence, the use of a calibration unit with a radio telescope is essential to improve the sensitivity of the telescope. It is worth mentioning here that a similar technique was used by a previous work to enhance the signal from two galaxies (3C348 and 3C353) [27]. Their findings are confirmed by this research, in the sense that the sensitivity of the telescope is enhanced when a unit calibration unit is used to observe astronomical sources.

In addition, a future work is planned to implement the image processing techniques in order to explore the radio signal from astronomical sources. This future work involves using techniques that are similar to those applied by previous studies [31].

Conflict of Interests Statement

The authors declare that they have no competing interests.

Acknowledgements

We would like to express our thank and gratitude to the head of the department of Astronomy and Space, academic staff, colleagues and all friends at the College of Science, University of Baghdad for their valuable advices and encouragement.

References

[1] L.T. Ali, Determination of the energy and kick velocity of crab nebula pulsar from the distribution morphology of the remnant, Iraqi J. Phys. 13 (2015) 144−150, https://doi.org/10.30723/ijp.v13i27.272.

[2] M. Ryle, The significance of the observation of intense radio-frequency emission from the sun, Proc. Phys. Soc. Section A, A62 (1949) 483−491, https://doi.org/10.1088/0370-1298/62/8/302.

[3] A. Unsold, Origin of the radio frequency emission and cosmic radiation in the milky way, Nature 163 (1949) 489−491, https://doi.org/10.1038/163489b0.

[4] M. Ryle, Radio Astronomy, Reports on Progress in Physics, 13 (1950) 184−246, https://doi.org/10.1088/00344885/135.

[5] H. Alfven, N. Herlofson, Cosmic radiation and radio stars, Phys. Rev. 78 (1950) 616−616, https://doi.org/10.1103/PhysRev.78.616.

[6] K.O. Kiepenheuer, Cosmic rays as the source of general galactic radio emission, Phys. Rev. 79 (1950) 738−739, https://doi.org/10.1103/PhysRev.79.738.

[7] G. Dubner, G. Giacani, Radio emission from supernova remnants, Astron. AstroPhys. Rev. 23 (2015) 1−48, https://doi.org/10.1007/s00159-015-0083-5.

[8] C.H. Mayer, T.P. McCullough, R.M. Sloanaker, Evidence for polarized radio radiation from the crab nebula, Astrophys. J. 126 (1957) 468−470, https://doi.org/10.1086/146419.

[9] D.A. Green, A Catalogue of 294 Galactic Supernova Remnants, Bulletin of the Astronomical Society of India. 42 (2014) 47−58, https://doi.org/10.48550/arXiv.1409.0637.

[10] M. Lyutikov, T. Temim, S. Komissarov, P. Slane, L. Sironi, L. Comisso, Interpreting crab nebula's synchrotron spectrum: two acceleration mechanisms, MNRAS 489 (2019) 2403−2416, https://doi.org/10.1093/mnras/stz2023.

[11] Y. Luo, M. Lyutikov, T. Temim, L. Comisso, Turbulent model of crab nebula radiation, Astrophys. J. 896 (2020) 1−13, https://doi.org/10.48550/arXiv.2005.06319.

[12] I. De Looze, M.J. Barlow, R. Bandiera, A. Bevan, M.F. Bietenholz, H. Chawner, H.L. Gomez, M. Matsuura, F. Priestley, R. Wesson, The dust content of the crab nebula, MNRAS 488 (2019) 164−182, https://doi.org/10.1093/mnras/stz1533.

[13] E. Mestre, E. Wilhelmi, D. Khangulyanm R. Zanin, F. Acero, D. Torres, The crab nebula variability at short time-scales with the cherenkov telescope array, MNRAS 501 (2021) 337−346, https://doi.org/10.1093/mnras/staa3599.

[14] G. Dubner, G. Castelletti, O. Kargaltsev, G.G. Pavlov, M. Bietenholz, A. Talavera, Morphological properties of the crab nebula: a detailed multiwavelength study based on new VLA, HST, Chandra, and XMM-Newton Images, Astrophys. J. 840 (2017) 1−12, https://doi.org/10.3847/1538-4357/aa6983.

[15] T. Martin, D. Milisavljevic, L. Drissen, 3D mapping of the crab nebula with SITELLE− I. Deconvolution and kinematic reconstruction, MNRAS 502 (2021) 1864−1881, https://doi.org/10.1093/mnras/staa4046.

[16] C. Wang, H. Li, K. Ying, Q. Xu, N. Wang, B. Duan, 1W. Gao, L. Xiao, Y. Duan, Active surface compensation for large radio telescope antennas, Int. J. Antenn Propag. 2018 (2018) 1−17, https://doi.org/10.1155/2018/3903412.

[17] J. Rhee, P. Lah, F.H. Briggs, J.N. Chengalur, M. Colless, S.P. Willner, M.L. Ashby, O. Le Fever, Neutral hydrogen (H I) gas content of galaxies at $z \approx 0.32$, MNRAS 473 (2018) 1879−1894, https://doi.org/10.1093/mnras/stx2461.

[18] K. Tisawech, P. Tummuangpak, K. Asanok, P. Jaroenjittichai, A sky survey of neutral hydrogen at 21 cm using NARIT 4.5m small radio telescope, J. Phys. Conf. 1380 (2019) 1−7, https://doi.org/10.1088/1742-6596/1380/1/012047.

[19] N. Namkham, N. Chanwedchasart, P. Jaroenjittichai, N. Prasert, The pointing model of 4.5-m small radio telescope at NARIT, J. Phys. Conf. 2145 (2022) 1−5, https://doi.org/10.1088/1742-6596/2145/1/012008.

[20] A. Pellizzoni, S. Righini, M. Iacolina, M. Marongiu, S. Mulas, G. Murtas, G. Valente, E. Egron, M. Bachetti, F. Buffa, R. Concu, G. Deiana, S. Guglielmino, A. Ladu, S. Loru, A. Maccaferri, P. Marongiu, A. Melis, A. Navarrini, A. Orfei, P. Ortu, M. Pili, T. Pisanu, G. Pupillo, A. Saba, L. Schirru, G. Serra, C. Tiburzi, A. Zanichelli, P. Zucca, M. Messerotti, Solar observations with single-dish INAF radio telescopes: continuum imaging in the 18 − 26 GHz range, Sol. Phys. 86 (2022) 1−30, https://doi.org/10.1007/s11207-022-02013-5.

[21] U.E. Jallod, K.M. Abood, Solar measurements for 21 cm wavelength using 3m radio telescope, Prog. Electromagn. Res. Lett. 85 (2019) 17−24, https://doi.org/10.2528/PIERL19041009.

[22] J.M. Marr, R.L. Snell, S.E. Kurtz, Fundamentals of Radio Astronomy Observational Method, Taylor & Francis Group, LLC, UK. 2016.

[23] L. Kong, T. Huang, Y. Zhu, S. Yu, Big Data in Astronomy Scientific Data Processing for Advanced Radio Telescopes, Elsevier Inc, UK. 2020.

[24] L. Pagani, D. Frayer, B. Pagani, C. Lefèvre, Radio telescope total power mode: improving observation efficiency, A&A 643 (2020) 1−7, https://doi.org/10.1051/0004-6361/202038976.

[25] T. Lauterbach, Radio Astronomy Small Radio Telescopes: Basics, Technology, and Observations, Springer Fachmedien Wiesbaden GmbH, Wiesbaden. 2022.

[26] C. Tan, Y. Yan, B. Tan, Q. Fu, Y. Liu, G. Xu, Study of calibration of solar radio spectrometers and the quiet-sun radio emission, Astrophys. J. 808 (2015) 1−20, https://doi.org/10.1088/0004-637X/808/1/61.

[27] A.A. Hammed, K.M. Abood, Observations results improvement using switching technique and source noise calibration unit, Environment and Sustainability, AIP Conf. Proc. 2437 (2022) 020182-1−020182-10, https://doi.org/10.1063/5.0092837.

[28] K. Neil, Single dish calibration techniques at radio wavelengthsNAIC/NRAO School on Single Dish Radio Astronomy ASP Conference Series, 2001 (2002) 1−18, https://doi.org/10.48550/arXiv.astro-ph/0203001.

[29] T. Wilson, K. Rohlfs, S. Huttemeister, Tools of Radio Astronomy, sixth ed., Springer-Verlag Berlin Heideelberg, Berlin. 2013.

[30] G. Pannuti, The Physical Processes and Observing Techniques of Radio Astronomy, Springer International Publishing, Switzerland. 2020.

[31] S. Hu, B. Lei, S. Wang, Z. Feng, Y. Shen, S. Wang, Bidirectional mapping generative adversarial networks for brain MR to PET synthesis, IEEE Trans. Med. Imag. 41 (2021) 145−157, https://doi.org/10.1109/TMI.2021.3107013.