Construction of a meteorological satellite data reception station for educational purposes

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ABSTRACT

This paper presents the construction of a satellite meteorological image reception station for educational purposes. The station was developed within the context of a semester-long extension course on electromagnetic wave propagation, within an undergraduate Physics program. The development of the station comprises the construction of the hardware (receiver, cables, and antennas) and the software pipeline required for image production. Signal cascades containing raw data received from the NOAA 15, NOAA 18, and NOAA 19 satellites during different observation sessions are presented. Based on these data, raw visible and infrared images, as well as processed images of clouds, temperature, and precipitation, were produced. Once completed, the station began to be used in non-formal education activities at a science center and was incorporated into the collection of experimental activities of the course from which it originated.

KEYWORDS: Science education. Space technology. Image processing.

1 INTRODUCTION

The Brazilian National Education Plan (PNE), approved by Law No. 13005, enacted in 2014, establishes twenty goals to be achieved within ten years from its publication and defines a set of strategies to be followed. Strategy 12.7 aims to "ensure that at least 10% (ten percent) of the total curricular credits required for graduation are dedicated to university extension programs and projects, prioritizing actions in areas of great social relevance" (Brasil, 2014, p. 6). Subsequently, in 2018, the National Council of Education established the Guidelines for Extension in Brazilian Higher Education and regulated the provisions set forth in Strategy 12.7 (Brasil, 2018).

In order to adapt the curriculum of its undergraduate programs to these legal provisions, the Federal University of Itajubá (UNIFEI) carried out a reformulation of its pedagogical projects. Among the various activities planned in this reformulation—programs, projects, courses, workshops, and events—are the extension-oriented courses whose full or partial workload is devoted to extension activities characterized as "interventions that directly involve external communities and are linked to the students' education" (Universidade Federal de Itajubá [UNIFEI], 2020, p. 417).

In this context, the new curriculum of the Bachelor's Degree in Physics program included, among other curricular components, an extension-oriented course entitled "Propagation of Electromagnetic Waves."[1] In this course, students must develop, throughout the semester, individually or in groups, a practical activity related to the course content.

This paper presents the practical activity developed by one of the students enrolled in the first offering of this course, whose objective was to construct a reception station for images from polar-orbit meteorological satellites (*Polar Operational Environmental Satellites* – POES) operated by the *National Oceanic and Atmospheric Administration* (NOAA). Since May 2022, this station has been used in non-formal education activities linked to Espaço InterCiências — a science center located on the UNIFEI campus (Silva; Cardoso; Monteiro, 2018).

2 METHODOLOGY

The development of this work was carried out in four distinct stages: hardware construction, software pipeline implementation, data collection, and image production. Figure 1 presents the sequence of signal processing from the satellites, from reception to image generation, in five main steps: (1) Acquisition, (2) Signal transformation, (3) Data reception, (4) Decoding, and (5) Final file. Each of these stages is presented in the signal processing flowchart shown in Figure 1.

Figure 1 – Signal processing flowchart.
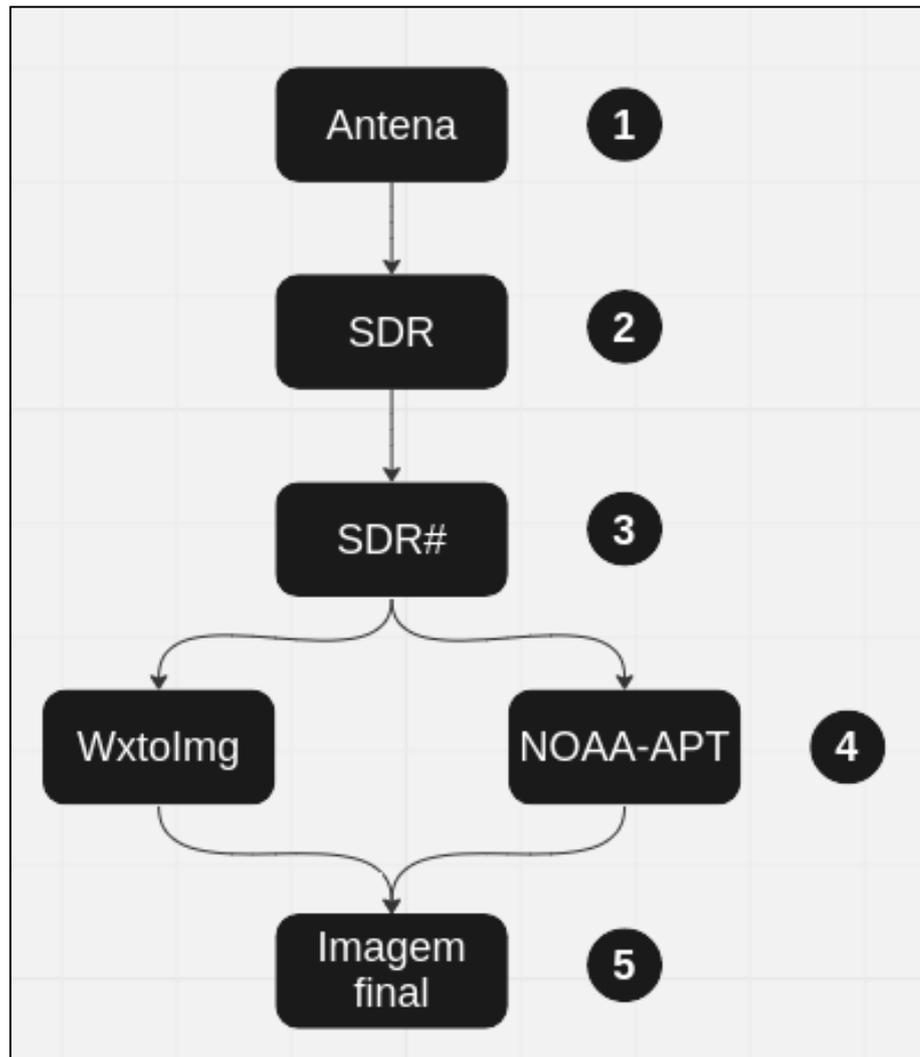
Source: The authors (2025).

2.1 Hardware

The NOAA-POES satellite constellation currently has four operational satellites transmitting in frequency modulation (FM): NOAA 15 (137.62 MHz), NOAA 18 (137.9125 MHz), and NOAA 19 (137.1 MHz). All satellites transmit signals with a bandwidth ranging from 30 to 40 kHz.

The hardware developed for the receiving station consists of three elements: an antenna, a coaxial cable, and a receiver, as shown in Figure 2. A laptop computer is responsible for processing the signal coming from the receiver.

Figure 2 – Assembled data reception station.

Source: The authors (2025).

Two antenna models were built: a dipole antenna with a 120° angle between the rods, and a double-helix antenna. This made it possible to compare the intensities of the received signals and determine which antenna type performs best for this kind of experiment. The results show that the dipole antenna exhibits greater sensitivity in data collection when compared to the double-helix antenna.

The ideal cable for this type of experiment is a coaxial cable with high data transmission capacity. However, such cables are not only expensive but also difficult to find on the market. Therefore, an RG-57 cable (the same used in residential installations for data reception from parabolic antennas) was employed, since the goal is to obtain image data and this cable offers high efficiency, low acquisition and replacement cost, and is easy to find.

To convert the signal collected by the antenna into a digital signal compatible with the computer, an SDR (Software Defined Radio) device manufactured by SDR-RTL.COM was used. This device is based on analog radio modulation and data-to-digital conversion technologies. Its spectral coverage ranges from 500 kHz to 1.75 GHz (Simple…, 2017).

2.2 Software

WXtoimg is the most comprehensive software for decoding data from the NOAA-POES satellite constellation. Among its main tools are: real-time decoding, cloud mapping, temperature mapping, 3D image creation, animations, automatic data collection, among others. Due to its high data extraction capacity, it is the most widely used software among individuals dedicated to satellite image reception as a hobby (WXtoimg, 2023).

The NOAA-APT software functions as a signal decoder using data from the .WAV file. To do so, the sampling rate is converted to 20,800 Hz. After processing and image generation, the geographical position where the data

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collection was carried out is determined, enabling the overlay of a map on the final image. Although it offers fewer features than WXtoimg, it is a more user-friendly solution (Bernardi, 2023).

SDR# is a software developed by the company Airspy, highly versatile for the reception and storage of radio signals. The software can graphically display the presence of radio signals across various frequency ranges, and it can also mark regions of interest, signal intensity, and record in mono or stereo modes, among other functionalities (AIRSPY, 2023).

2.3 Description of the observations

Data collection was carried out at the main campus of the Federal University of Itajubá (UNIFEI). The location that showed the best performance was the university's soccer field. This is due to its position, as it is distant from buildings and large constructions responsible for most of the noise present in the images.

The prediction of the satellites' passage time and their trajectory across the sky, allowing directional tracking of the received signal, was carried out using the Heavens Above application (PEAT, 2023). This free software calculates the satellite's horizontal coordinates (azimuth and elevation) from its Keplerian elements and the geographical coordinates of the observation site.

In each orbit, the altitude of the NOAA 19 satellite ranges from 839 km to 860 km above sea level. Its orbital period is 1 h 42 min, and the inclination of its orbit relative to the equatorial plane is 99°. The maximum elevation of each pass relative to the observer's horizon is not constant. Therefore, the time the satellite remains above the horizon during each pass is also variable. To obtain good images, it is recommended to prioritize higher passes, during which the satellite remains above the horizon for up to ten minutes, and ground or building noise is minimal. However, acceptable images can also be obtained from passes lasting five to six minutes.

To test the influence of weather conditions on the reception of satellite-transmitted data, data collection sessions were carried out under different conditions: clear, cloudy, and rainy skies. The results indicated no significant difference in data quality under these circumstances. This is because the wavelength is long enough to pass through clouds without being significantly scattered or absorbed.

After determining the data collection site, calibrations were performed to determine the receiver's sensitivity. This step is important to ensure that even weak signals can be detected. For this purpose, local broadcast sources were used, such as stations operating in the commercial FM band (88 MHz to 108 MHz).

Once these stations could be detected, the receiver was ready to collect meteorological satellite data, since, in the test runs, the signal perceived by the receiver reached an amplitude of 15 dB relative to the background noise.

Figure 3 – Signal waterfall from the NOAA-19 satellite.
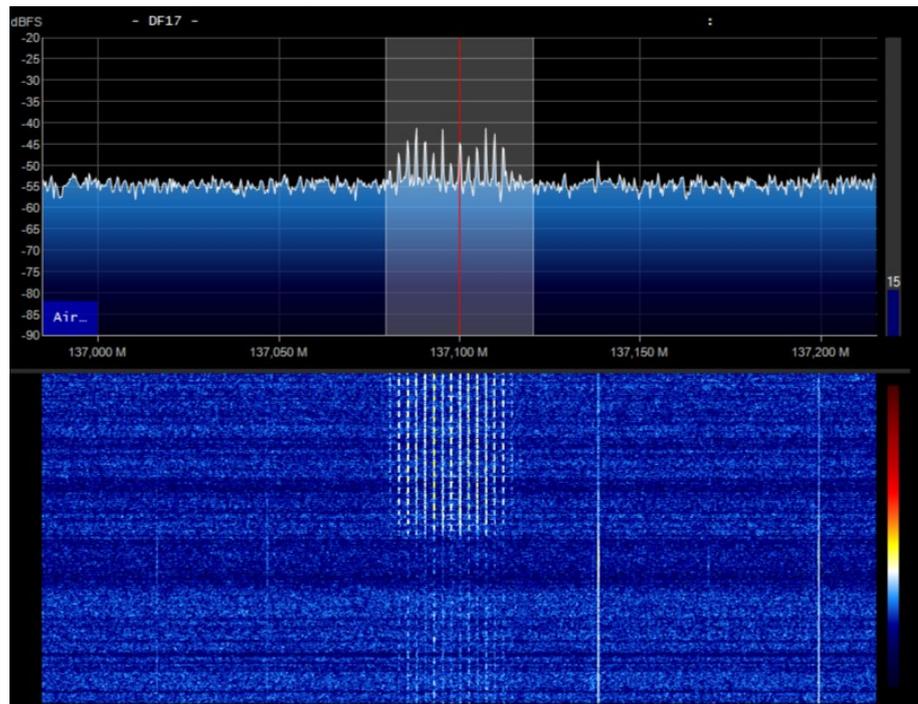
Source: The authors (2025).

Figure 3 shows an example of a NOAA-POES satellite signal collected using the SDR# software. The most intense peaks correspond to the signal captured by the antenna — the higher the peak, the cleaner the signal will be in relation to the noise (the continuous background signal across the entire image) and its respective intensity scale in dB. In the lower part of the image, it is possible to see the signal waterfall, which highlights the signal in color scales over time: the bottom portion represents older signals, while the top represents more recent ones.

It is important to note that signal intensity varies according to the detector's sensitivity. Antennas with higher gain (such as directional ones) may present better signal-to-noise ratios.

3 RESULTS AND DISCUSSION

During the observations, it was necessary to select a modulation type of *Wide Frequency Modulated* (WFM), since the transmission bandwidth (approximately 40 kHz) is similar to that of a commercial FM radio station. To store the data, the stereo audio output was recorded, as each side of the audio corresponds to one image data channel. For recording, the native recording tool of the SDR# software was used, and the file was exported in .WAV format.

After decoding the audio with the software tools (NOAA-APT and WXtoimg), it is possible to access the raw data transmitted by the satellite. To illustrate, we present the data processed using WXtoimg, as it offers more tools for analysis.

Figure 4 – Raw image from the NOAA-19 satellite in two bands: (a) infrared (left image) and (b) visible (right image).
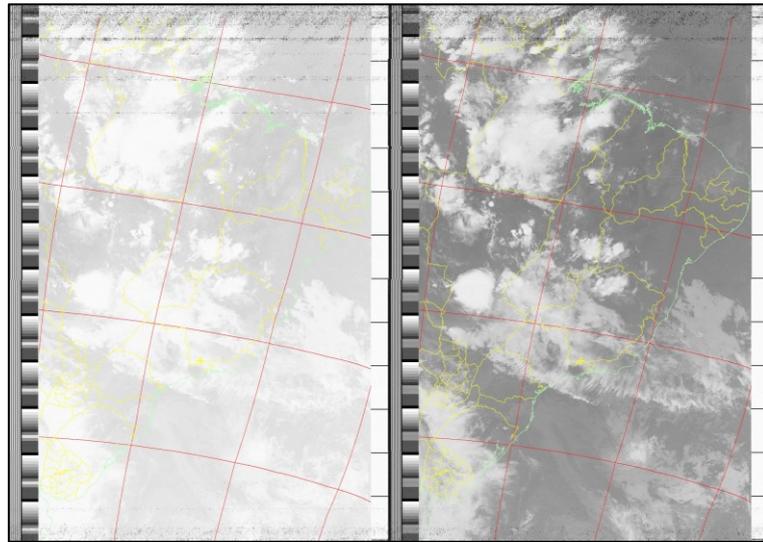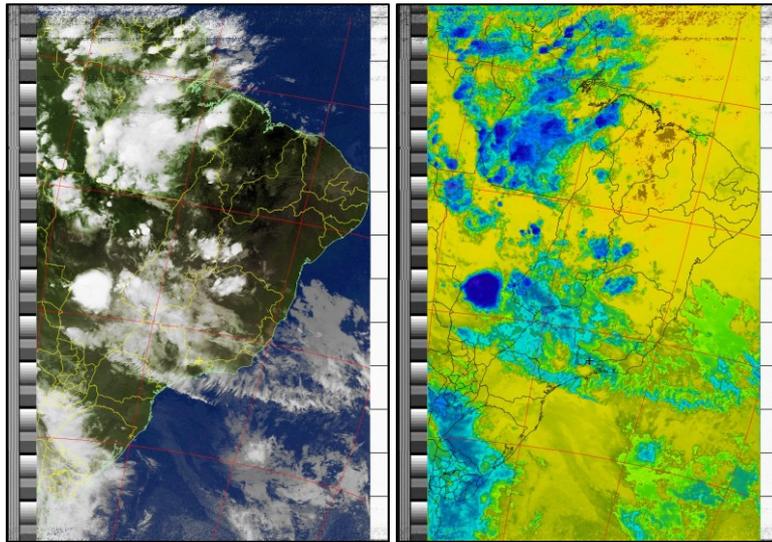

Source: The authors (2025).

In Figure 4, it can be seen that the NOAA-19 satellite transmits information through two channels. These are generated by sensors that operate in the visible and infrared ranges, and the transmission of these information bands depends on the time of the satellite's passage over a given region. For example, during the first daily pass (morning), images captured in both the visible and infrared ranges are transmitted, whereas during the second pass (nighttime), only images from the infrared sensors are transmitted.

The NOAA satellites have five data channels, each with a specific function (ranging from cloud mapping to forest monitoring). The first one (channel 1) is responsible for data collection in the visible range, which makes it dependent on sunlight reflection from the Earth's surface for its operation. The remaining channels operate in the infrared range and are therefore independent of sunlight for data collection (NOAA, 2009).

It is also possible to observe three vertical bars extending along the entire image. These bars are information codes that can be read by decoding software to generate other maps, as shown in this section. The white bar on the right side of each information channel is called a timestamp, in which each white block represents one minute of data transfer. On the left side of the channel, the blocks in various shades of gray correspond to information channels that provide key data points, such as temperature in the image. Finally, the band in the middle of the image indicates the separation between the transmission channels.
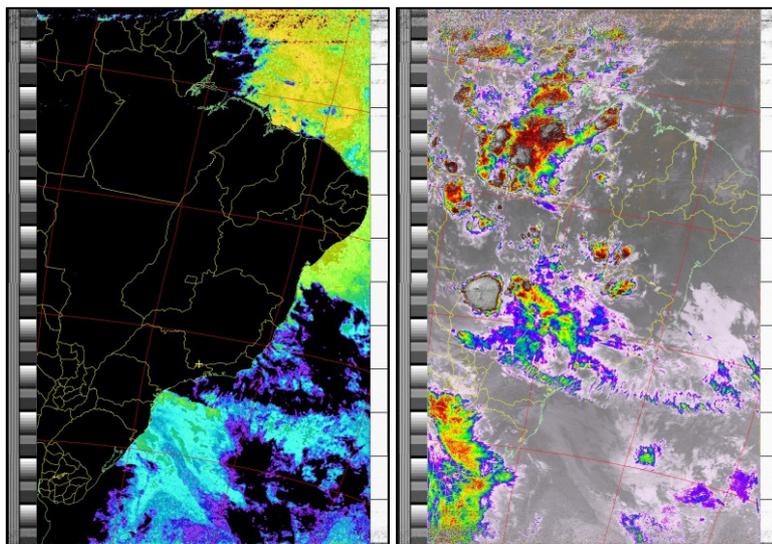
Using the tools available in the WXtoimg software, it was possible to construct additional maps, such as those shown in Figures 5 and 6.

Figure 5 – NOAA-19 satellite maps: (a) clouds (left image) and (b) temperature (right image).

Source: The authors (2025).

Figure 6 – NOAA-19 satellite maps: (a) ocean temperature (left image) and (b) precipitation (right image).

Source: The authors (2025).

In Figure 5a, the projection of clouds over the map of South America can be observed, with colors already predefined in the system. The information that can be obtained from this image concerns the cloud coverage present at the moment when the satellite passed over the region.

Figure 5b shows a surface temperature map. In this map, the regions marked in orange and red represent areas with higher temperatures, while the regions in blue and violet represent areas with lower temperatures.

In Figure 6a, the temperature scan for the oceans can be seen. The interpretation of these data is similar to that of Figure 5b, but this time optimized exclusively for the oceanic region.

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Figure 6b shows a map indicating rainfall incidence, where regions in reddish tones represent more intense clouds and, consequently, a higher probability of precipitation. The opposite is also true: the gray-colored regions indicate areas where there are either no clouds or an insignificant amount of clouds.

The NOAA-19 satellite was chosen as the main satellite for this round of data collection because it is the latest satellite of its generation to be launched, which ensures greater stability and signal transmission quality. However, other similar satellites are still in operation, such as NOAA-15 (Figure 7) and NOAA-18 (Figure 8), which transmit at 137.6200 MHz and 137.9125 MHz, respectively. These figures were generated using the NOAA-APT software.

Figure 7 – Raw image from the NOAA-15 satellite in two bands: (a) infrared (left image) and (b) visible (right image).
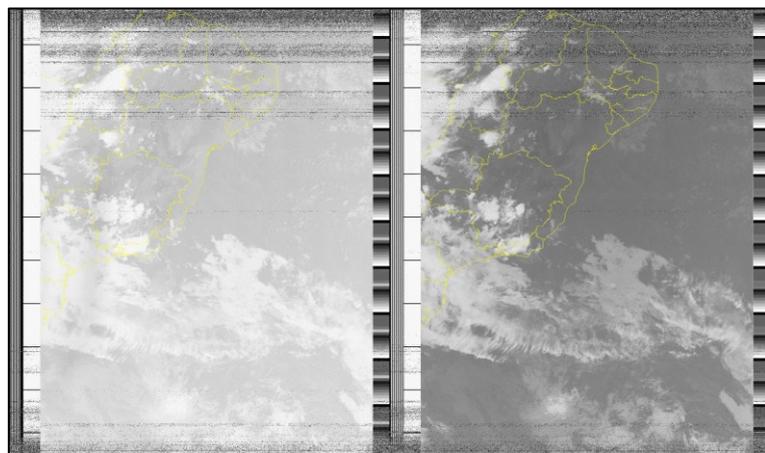
Source: The authors (2025).

Figure 8 – Raw image from the NOAA-18 satellite in two bands: (a) infrared (left image) and (b) visible (right image).
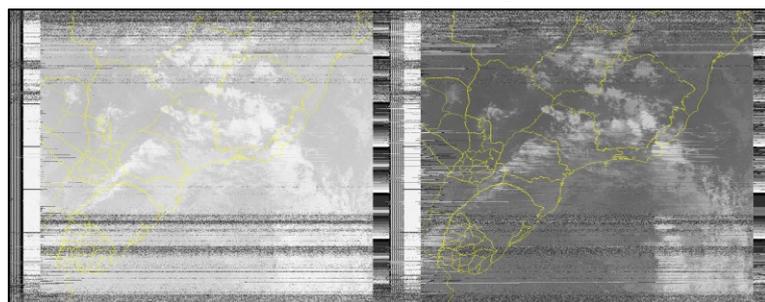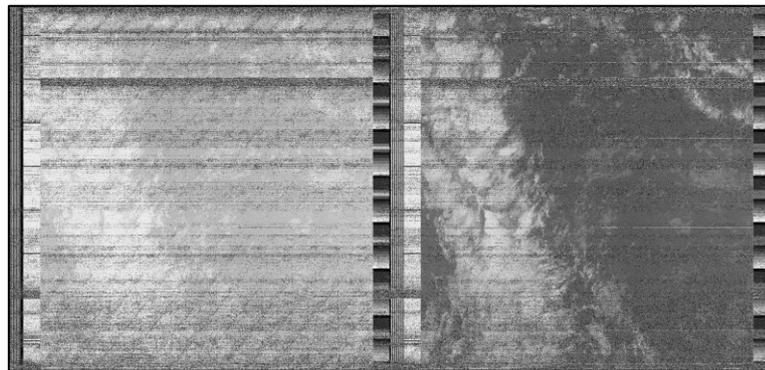

Source: The authors (2025).

Table 1 and Figures 9, 10, and 11 illustrate the effect that the maximum altitude has on the quality of the produced images. These images were generated from observations made on the UNIFEI campus using the dipole antenna. Figure 9 corresponds to an observation of the NOAA-19 satellite at a maximum altitude of 26°, while Figure 10 shows an altitude of 44°. In Figure 11, the maximum altitude was 85°, meaning the satellite passed close to the zenith.

Table 1 – Image quality as a function of maximum altitude.

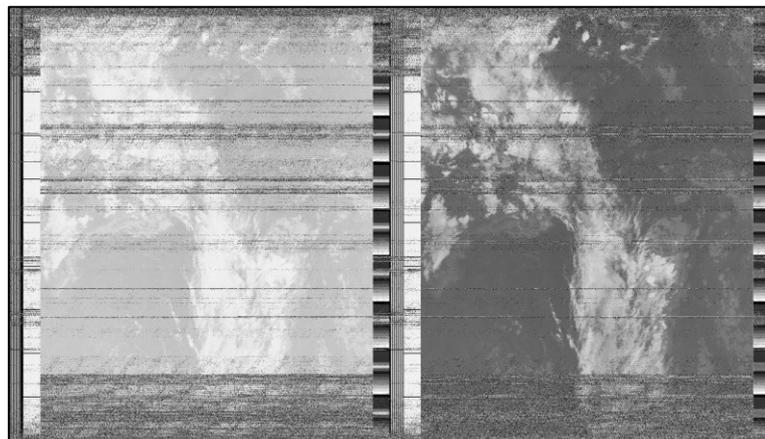| Passage altitude	Classification
From 0° to 30°	Low
From 31° to 60°	Medium
From 61° to 90°	High

Source: The authors (2025).

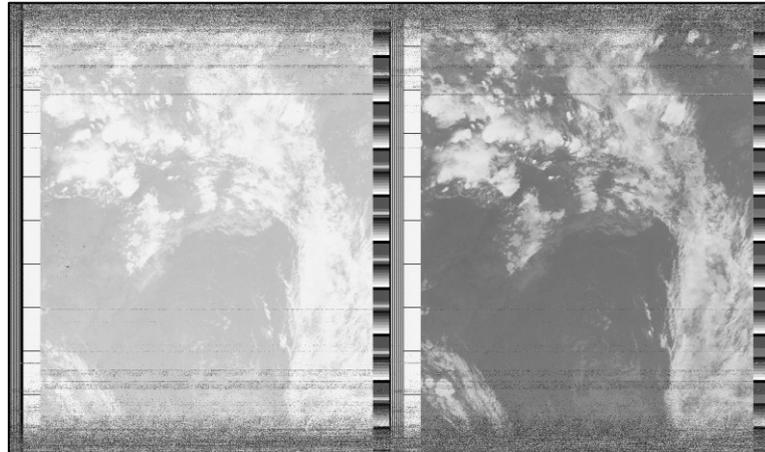Figure 9 – NOAA-19 Satellite Pass (26° – Low).

Source: The authors (2025).

Figure 10 – NOAA-19 Satellite Pass (44° – Medium).

Source: The authors (2025).

Figure 11 – NOAA-15 Satellite Pass (85° – High).

Source: The authors (2025).

It is possible to notice a significant difference between image quality and the satellite's maximum elevation during its pass. This occurs because, at lower elevation angles, many factors can influence the quality of the captured data. Perhaps the most relevant is the presence of buildings and the terrain profile near the receiving station.

Taking as an example a pass with a maximum elevation of 26°, Figure 12 shows that a 30-meter-high building (approximately ten stories) can interfere with data reception, even when located 61 meters away from the receiving station. In this example, the line connecting the satellite to the receiver (also known as the line of sight) is blocked by the building. Therefore, the signal reaching the receiver is affected by interference and diffraction, which degrades the image quality.

Figure 12 – Illustration of signal obstruction.
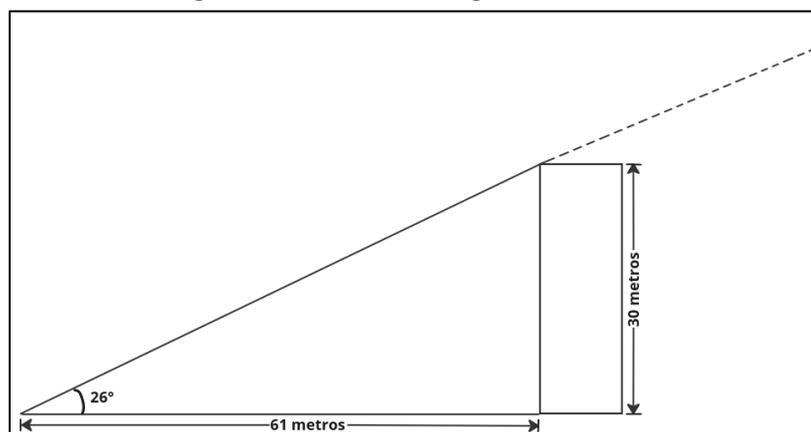
Source: The authors (2025).

One possible way to overcome this problem is by installing the receiving antenna in locations where the line of sight is unobstructed, ensuring that the antenna's reception field is free from interference and that data collection presents the best possible signal-to-noise ratio.

4 CONCLUSION

The station described in this work began to be developed within the context of an activity linked to an extension course in the Bachelor of Physics program at UNIFEI. After the end of the course, its development continued as a Scientific Initiation research project. The complete process consisted of building all the hardware (receiver, cables, and antennas) and the software pipeline, which ranges from collecting raw data to producing the final product — the meteorological images.

Once completed, the station started to be used in non-formal education activities aimed at the community outside the university and was incorporated into the collection of experimental activities of the undergraduate course that originated it.

Among the difficulties encountered during the experiment, perhaps the greatest was obtaining the SDR. However, with the popularization and lower cost of electronic component production, this device can now be found in various retail stores as well as in e-commerce platforms. All other materials, such as coaxial cables used in televisions, antennas, and computers, are easier to find.

Building the station proved to be a challenging yet highly promising project (both technically and educationally), considering the application of several Physics concepts, such as electromagnetic wave interference (and its effects on data transfer), Doppler effect, resonance, electromagnetic spectrum, orbital mechanics, and climate studies.

It is also worth highlighting that, given the new legal requirement that at least 10% of undergraduate course credits must be completed in university extension programs and projects, there has been a substantial increase in the importance given to extension activities within curricular projects. In this sense, the implementation of experimental activities, such as the one presented in this work, exemplifies how the articulation between extension and undergraduate education can enhance the teaching of Physics from an integrative perspective.

However, it is important to note that this type of approach presents considerable challenges. To overcome them, experimental activities must not be limited to a conception of a didactic laboratory characterized by practical classes following a fixed script, conducted in a specific place, and with a predetermined duration.

CONSTRUÇÃO DE UMA ESTAÇÃO DE RECEPÇÃO DE DADOS DE SATÉLITES METEOROLÓGICOS COM FINALIDADE EDUCACIONAL

RESUMO

Este trabalho apresenta a construção de uma estação de recepção de imagens de satélites meteorológicos com finalidade educacional. A estação foi desenvolvida no contexto de uma disciplina extensionista semestral que versa sobre a propagação de ondas eletromagnéticas e é vinculada a um curso de graduação em Física. O desenvolvimento da estação compreende a construção do hardware (receptor, cabos e antenas) e do pipeline do software necessário à produção das imagens. São apresentadas as cascatas de sinais com os dados brutos recebidos dos satélites NOAA 15, NOAA 18 e NOAA 19 em diferentes sessões de observação. A partir desses dados foram produzidas imagens brutas no visível e no infravermelho, imagens processadas de nuvens, temperatura e precipitação. Uma vez finalizada, a estação passou a ser usada em atividades de educação não-formal em um centro de ciências e foi incorporada ao acervo de atividades experimentais da disciplina que lhe deu origem.

PALAVRAS-CHAVE: Educação em ciências. Tecnologia espacial. Processamento de imagens.

NOTES

1 A preliminary version of this research was presented at the 5th Scientific Initiation Symposium of the Federal University of Itajubá in 2022.

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