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DATASAT – ADA Ground Station Network. Automatic Directional Antenna for Space Communications on LEO Spacecrafts

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Abstract

This article presents Ground Stations network (DATASAT) designed and developed in Brazil to perform automatically satellite telemetry, tracking and command. Each station that forms the DATASAT network, called Automatic Directional Antenna (ADA), is composed of an external module, which contains the pointing mechanism and antennas, and an internal module that contains the controller, the signal receiver and the computer with TT&C, signal processing and information dissemination software that enables Data and Command Center to be accessible via the Internet. This solution, open-source software development, composes the DATASAT Stations Network (http://datasat.space), which aiming the partnership with Public and Private Institutions, to use it in their bases for Teaching and Research without charge. The architecture of ADA, its elements and lessons learned from the design, assembly and integration of the Ground Station are described. DATASAT / ADA success lies in its operability, which allows satellite tracking automatically at low cost as well as optimization of signal capture, encryption, data compression and storage data, allowing integration with client systems, remote control, providing technology and know-how to support different research or commercial projects that require a Ground Stations Network.

Keywords: ground-station, antenna, network, telemetry, tracking

1. INTRODUCTION

Space activities, products and services increasingly represent an important segment in the economic and social development of various countries (Schmidt, 2011). The last decades have been marked by space exploration that can be considered a global common good and, therefore, important for many economies.

In this segment, satellites and their variations can be considered the main axes of space activity and play a major role in today's world with space applications involving, mainly, Earth observations, telecommunications, navigation and positioning system, meteorology and scientific research. However, the satellite is one of the components of a space mission. In the various space missions involving satellites, and in their different sizes, in low, medium or high orbits, they need ground bases so that they can be commanded and ground stations play this important role for telemetry, trace and command of a space mission.

A typical space mission is composed of one or more spatial segments, characterized by the spatial object that can be a satellite and its variations or a probe, and one or more ground station, consisting of hardware and software infrastructure resources in addition to the procedures for preparing and executing mission operations that are fundamental, according to (Carniello et al., 2005).

In recent years, the number of space missions has increased in the world, given the numbers of the global satellite industry. According to the Satellite Industry Association report (TAURI group, 2018), the international space market had an average growth of around 3% between 2017 and 2018, with global profits of around USD 277 billion, see in Figure 1.

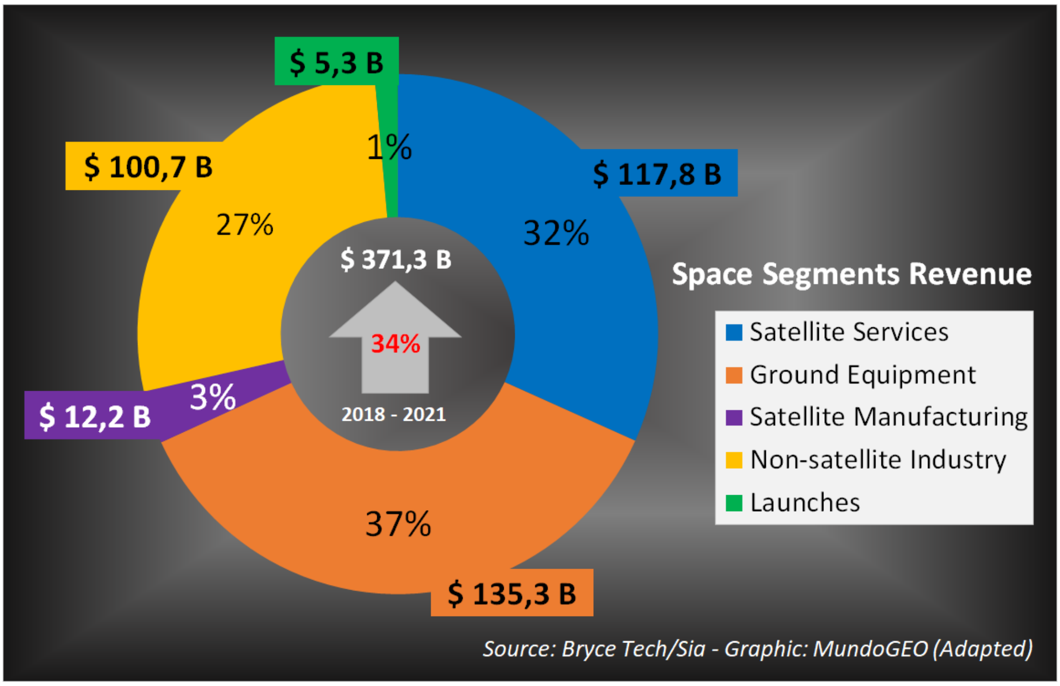


Figure 1 – Global Space Industry (In Billions of Dollars, in 2020)

This growth, in part, was driven by the Small Satellite industry and can be classified, according to (NASA, 2017) in Table 1. This market was valued at $1.340 million in 2018 and is estimated to reach US$ 6,280 million in 2025, with a composite annual growth rate (or CARG) of 21.4% during the forecast period, according to the study (The Market Reports, 2019) that considered 2018 the base year and 2019 to 2025 the forecast period.

Specifically with regard to nano satellites and microsatellites, according to (SpaceWorks, 2019), it is predicted that "294 nano/microsatellites will be launched in 2019, representing an increase of 17% compared to 2018" and still estimates that 2,000 – 2,800 nano/microsatellites will be launched in the next 5 years.

Table 1 – Small Satellites

Satellite Class	Mass Variation
Minisatellite	100-180 kg
Microsatellite	10-100 kg
Nanosatellite	1-10 kg
Picosatellite	0.01-1 kg
Femtosatellite	0.001-0.01 kg

In the Nanosatellite classification, the CubeSat is included which is characterized by the standard size of 10 x 10 x 10 cm, i.e. a unit or 1U, and can be extended to larger sizes: 1, 2, 3, 5, 6 and up to 12U. Originally developed to provide a platform for education and space exploration, it developed its own industry, with government, industry and academia collaborating for increasing capabilities. CubeSat provided, mainly, an economic platform to scientific research, new technology demonstrations and advanced mission concepts, including constellations.

According to (Baldini, 2018), CubeSat began performing tasks similar to those performed by large satellites, however at more affordable costs and therefore they have been increasingly used for space research, amateur communications and recently in commercial applications.

It is observed in the scenario described, until then, the evolution of satellite technologies and spatial mission requirements, which constantly increases the need for ground stations technologies and access networks.

According to (Cutler et al., 2002), space missions are intensely requiring increased coverage and access opportunities. The space mission on-demand access requires space resources to be used when needed and no longer only when scheduled. Furthermore, information between spatial objects and end users tends to be end-to-end, that is, without intermediaries, requiring network interfaces and spatial systems connected to the Internet. In addition to the synchronism of operations, when several spatial objects are captured in the visibility of the access network.

It is noteworthy, according to the same author that a spatial mission tends to require a high level of autonomy, that is, operational centers controlled by people, but mainly by software since, according to (Carniello et al., 2005), automation could reduce the projects costs. Added to this, according to (Baldini, 2018), the substantial increase in number of institutions that are building satellites and space systems that require the use of access networks. Finally, (Cutler et al., 2002) considers that the trend of future space missions is to require ground station infrastructure to support legacy equipment and new technologies.

As regards the points presented, it is understood that technologies related to ground stations must progress to meet future demands. Currently, many missions involving satellites or their variations in low orbit are limited to one or two ground stations for scheduling and tracking, controlling and receiving data and still having stations that do not support a 24/7 access demand.

It adds here, according to (Baldini, 2018), that the biggest research efforts are in the space segment, as professionals in the "aerospace area have greater interest in on-board systems, and problems related to satellite flight dynamics". However, without a ground station establishing the link between the satellite and these professionals, who have an interest in the payload data, the mission will not be performed. The University research groups rely on third parties to obtain data from their own mission and often use communication systems in the amateur radio range taking advantage of stations around the world. The dependence of radio amateurs is not at all bad, can be used as a very special condition, but often it cannot be haven a standard of data received, and so little can be counted on regular activities.

Developing the ground station itself consumes financial resources and often the station is idle most of the time. Optimizing a performance-efficient ground station is something that involves a lot of experimentation and enhancements. As an aggravating factor, the average period of communication between the ground station and space vehicles is restricted to minutes per day.

To combat these limiting factors, ground stations networks can be developed, so that the possible time of communication is extended to hours per day, depending on the location of the chosen stations and orbits.

Other climatic and local factors, where stations are located, can also be optimized such as the geomagnetic failure of the South Atlantic (or South America), the compensation of solar activity, among others under study.

Obviously, communications with satellites can have an impact of atmospheric conditions causing loss of contact with the ground station. One solution to work around the problem is for the satellite to connect, or be viewed, to multiple stations in different geographic locations so that they can track it, and it is therefore crucial to increase the number of stations installed on the Earth's surface. Another point that reinforces DATASAT, is the increase of satellites in orbit, missions that comprise two or more satellites acting together and those where there are transmissions in different frequency ranges.

As cited by (Cutler et al., 2002), there are several satellite communications networks such as NASA's Tracking and Data Relay Satellite System (TDRSS), which provides coverage to a range of missions, from geostationary satellites to low-orbit satellites, however, the physical and cost restrictions of transceivers (such as power, weight, and antenna positioning) are prohibitive for many space missions.

GENSO – Global Educational Networks for Satellite Operations – is an initiative focused on educational space missions, which integrates a worldwide ground station network and satellite and their variations that can interact through standard Internet-based software aimed at increasing the return of space missions.

The GENSO system, among other features, offers the ability to plan and schedule the ground station allocation to missions maximizing network efficiency and meeting mission requests. In a high-level view of architecture, the system focuses on a central component tasked with managing mission requests and scheduling ground stations allocations. In this context, space missions are users while ground stations are the resources.

There is also the SatNOGS – Satellite Network Open Ground Stations – a project that, according to (White, D. 2018) promotes and supports free and open spatial applications seeking to solve the problem of connecting many satellite users/observers to many ground station operators. It is used modern techniques related to free software, web and hardware in the implementation of network, database, client and ground stations. The system modularity allows the dual use of registered ground station, that is, allows a user to request satellite observations from a given station and the station owner can use it for his own purposes. The requests do not interfere with the local operation and, additionally, use the large amount of time that a civil and non-commercial ground station would be idle.

Another project, which is commercially purpose, is Leaf Line (Pandolfi et al., 2016), developed jointly by Leaf Space and Institut Supério des Sciences et Techniques da Univertié de Picardie Jules Verne. This project develops the implementation of a ground stations network operating on VHF, UHF, S Band and X Band frequencies for tracking and command nanosatellite and microsatellite and thus the mission´s professionals focus on their end activity and are released from concern with ground station and its high costs. In addition, it considers the autonomous status of the station and the capacity of a cloud network. These are talented initiatives, but the cost can be prohibitive, monitoring may not be regular, the antennas may not be standard and may compromise the quality of data collection, moreover, not all frequency ranges can be reached.

The purpose of this work is to present the solution for ground stations network, DATASAT, in order to track nanosatellites and microsatellites, to send remote controls and to receive signals. Such stations will consist of the same standardized equipment set, where the main component will be the ADA (Automatic Directional Antenna), developed by CRIAR SPACE SYSTEM Company and composed of a remote and automatic antenna steering mechanism and an antenna set optimized for various frequencies, as well as an automation and scheduling architecture station operations.

The objective is to distribute units of this ground station in the Brazilian territory and other countries, as in Portugal, where the Company has a subsidiary. It is also intended that the distribution of DATASAT, take the way through partnerships with educational institutions.

2. ADA - AUTOMATIC DIRECTIONAL ANTENNA

Ground stations are designed to provide real-time communication with satellites. They send radio signals to the satellite (uplink), receive data transmissions (downlink) and, in some cases, serve as the command-and-control center for the satellite network. The features desired in ground stations or in their equipment set are mainly command and control functions, satellite health monitoring system, tracking system and instant location (latitude, longitude and altitude), as well as systems that allow retransmission of data captured for interested users and possibility of remote control.

Currently world players offer equipment with related features, however at a high cost, in addition to Brazilian researches import them through a slow process. Nations with strong economies and robust scientific systems are the same as they are at the forefront of the space systems development. The purchase of certain equipment and systems essential to the development of space activities makes countries partially dependent on a particular manufacturer, because moving from one system to another can involve high costs.

In order to have low cost and technological independence in relation to the world players, the ADA (Automatic Directional Antenna) was conceived to be part of a ground station that, together with other Units of the ADA, will form the ground stations network, DATASAT.

ADA is an automatic antenna steering system, composed of motors set, reducers and controller, which receives coordinates for positioning and is able to point its antennas at the object from which captures or sends signals, and this object can be a probe or satellite, and its variations. The set connects to a computer that has signal capture equipment and control software, ADASERVER. With movement in elevation, in a dome from 0º up to 90º, and azimuth from 0º to 360º, the ADA can point an antenna connected to it in any direction, capture its signals and make them available to interested users.

When considering the state of the art of ground stations evaluated for small satellites, with emphasis on CubeSat, it was chosen to equip ADA to operate on VHF, UHF, S Band and X Band frequencies. VHF and UHF antennas have already been built and tested. In the following tables the antennas specifications can be checked:

Table 2 – Example of YAGI VHF Antenna

Example of YAGI VHF Antenna	
Type	Double Yagi VHF
Elements	10
Frequency Range (RX)	136 - 149 MHz
Frequency Range (TX)	144 - 148 MHz
Size	4,5 m
Weight	3,100 kg
Beam Width	39°
Gain	18 dBi

Table 3 – Example of YAGI UHF Antenna

Example of YAGI UHF Antenna	
Type	Double Yagi UHF
Elements	12
Frequency Range (RX)	425 - 455 MHz
Frequency Range (TX)	430 - 440 MHz
Size	3 m
Weight	1,600 kg
Beam Width	18° - 20°
Gain	14.5 dBi

Signal reception and transmission, or downlink and uplink, are done through SDR – Software-Defined Radio – which, according to (Ceylan et al., 2016), SDRs are flexible and can be reconfigured without hardware changes. They are also remotely updated making them advantageous compared to traditional analog radios as SDR requires fewer (or no one) analog components.

Moreover, to ensure low costs in the operation of the ground station equipped with the ADA, there is ADASERVER, with features that minimize human effort in operation. According to (Carniello et al., 2005), the automation of the ground segment allows reduction of expenses with spatial mission planning and operations teams, in addition to "increasing the reliability of the execution of space operations through the reduction of the probability of human failures”.

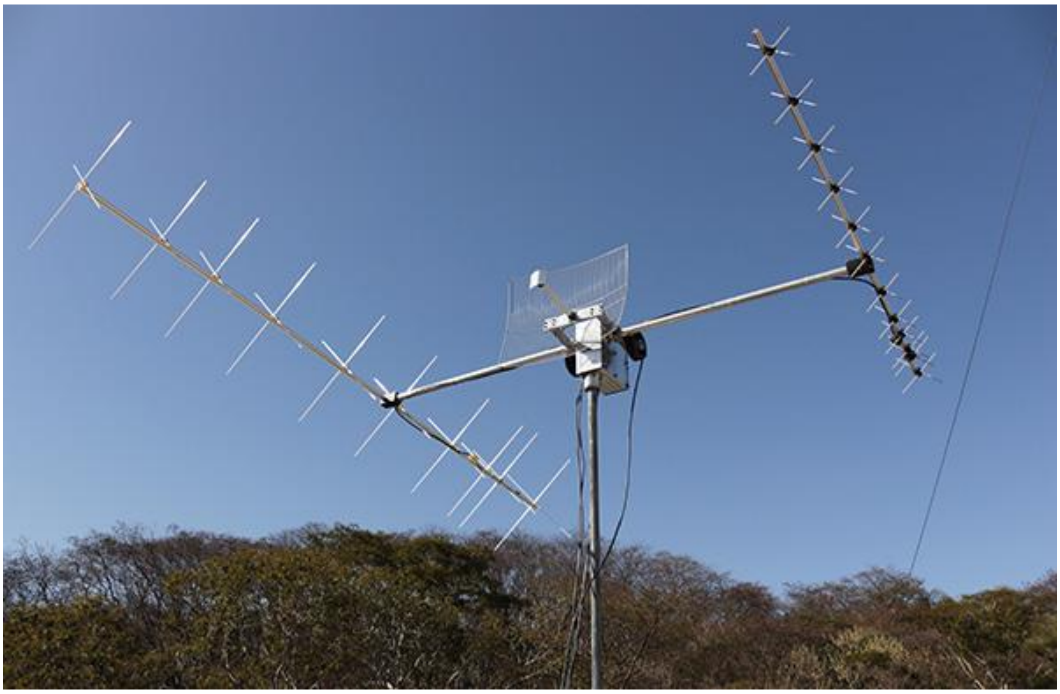


Figure 2 – ADA installed

An installed unit can be seen in Figure 2 and the ADA main specifications are:

- Ability to position the antenna in any direction, considering azimuth from 0° to 360° and elevation from 0° to 90°;
- Ability to position the antenna with accuracy of 0.1°;
- Reducer system capable of producing a torque of 480 kgf x cm, being possible to rotate/raise antennas with up to 12 kg distributed.

The system is coated with seals, sensors and parts, which ensure protection against weather ing, smooth and quiet operation and without the need for constant maintenance.

The benefits that ADA provides are:

- Affordable cost;
- Top quality product;
- Easy installation;
- Simple operation;
- Satellite automatic tracking that can be previously scheduled;
- Remote operation and data acquisition control.
-

2.1. Functional Diagram

The ADA was designed modularly in order to simplify the assembly, installation and allowing electromechanical and electronic requirements to be met. The External Module consists of the antennas set and the motors and reducers that are part of the positioning system. The Internal Module comprises the antenna positioning system controller and ADASERVER that commands/receives the signal sent/captured by the antenna, according to Figure 3, and which can be operated remotely.

The positioning system controller was developed to drive the motors and reducers to position the antennas toward the target when passing from azimuth coordinates and elevation received from ADASERVER. With this, the antenna will be able to follow the target along its orbit and accurately in motion.

While ADASERVER sends the azimuth and elevation coordinates to the positioning system, it also tunes the SDR frequency to command and receive the target signals, that is, the satellite and its variations or the probe.

Basically, there is:

1 – From the satellite registration in NORAD – North American Aerospace Defense Command – there is the automatic determination of its positioning through the orbital elements in TLE – Two Lines Elements – pattern, or it be possible to enter the elements manually.

2 – From the satellite choice and its frequency of uplink and downlink, the ADA automatically points to the target continuously during its passage, corrects the Doppler Effect, receives telemetries and sends the remote controls. The information receipt is recorded in file with the respective monitored satellite ID or commands sent according to its encoding. Remote controls sending encoding is by command line or text file contained the command list, or command via TCP/IP.

3 - The file contained the information received and sent commands can be read remotely.

4 – Data received and processed can be stored and distributed in a Data Center available on the Internet.

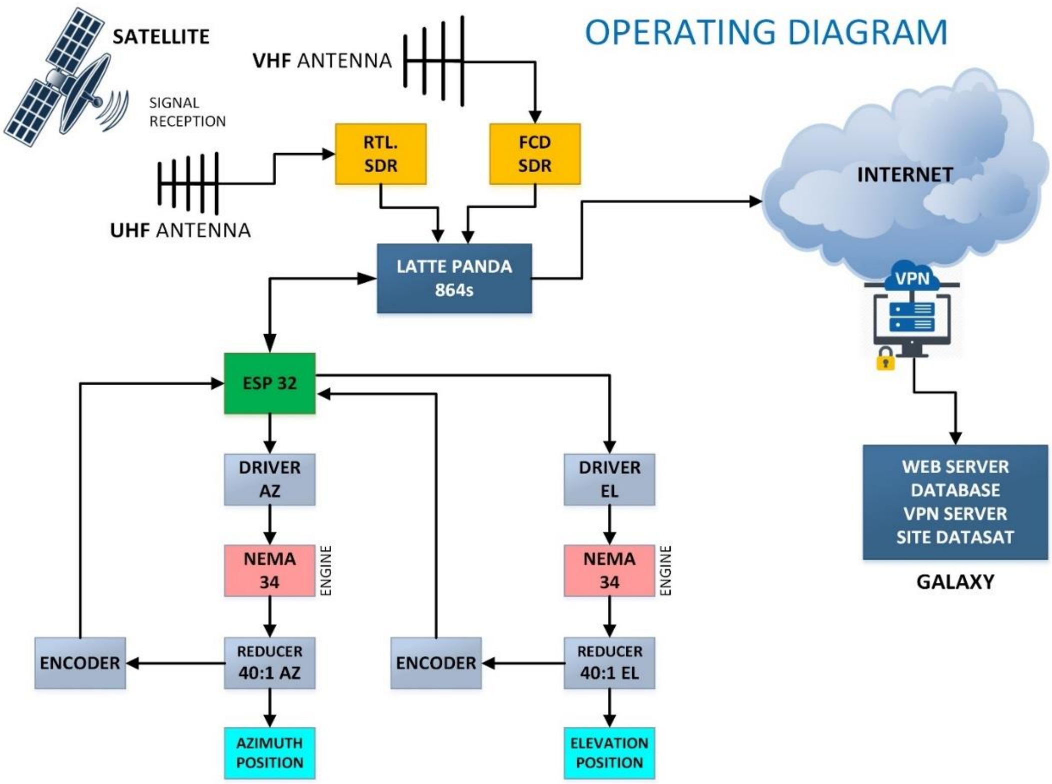


Figure 3 – Functional and operating diagram

2.2. Antenna Automatic Steering System

The ADA's automatic steering system uses a mechanical driver driven by a gear motors system empowering the antenna to follow satellite, and its variations, accurately in movement along its orbit, following the trajectory calculated and whose pointing coordinates are sent at regular intervals to the engine. The geometry chosen for the project was "elevation on azimuth" type, because it is simple and by the direct relationship between the positioning angles and the coordinates used for antenna steering.

The system consists of gear motors set, moving simultaneously in azimuth and elevation. Precision stepper motor is used, due to its simplicity of control, both in positioning and speed, because this type of motor performs its displacement at precise angles, which are directly proportional to the pulses sent to the driver as well as its speed can be controlled through pulses frequency. Thus, the control can be performed without the need for a feedback circuit (closed loop), which makes the cost of the application lower.

Below is the external module specifications and Figure 4,5,6 and 7 shows the details of the mechanical part and dimensions.

Table 4 – External Module

External Module	
Maximum Current	7.2 A
Turning Angle	Azimuth: 0° - 360° Elevation: 0° - 90°
Maximum Rotation Speed	Azimuth: 22.5°/s (Moving 360°) Elevation: 22.5°/s (Moving 90°)
Precision	+/- 0.1°
Size	Width: 491.28 mm Length: 3,214.15 mm Height: 1,351.40 mm
Weight	49,300 kg

Figure 4 – ADA mechanical elements – Front view

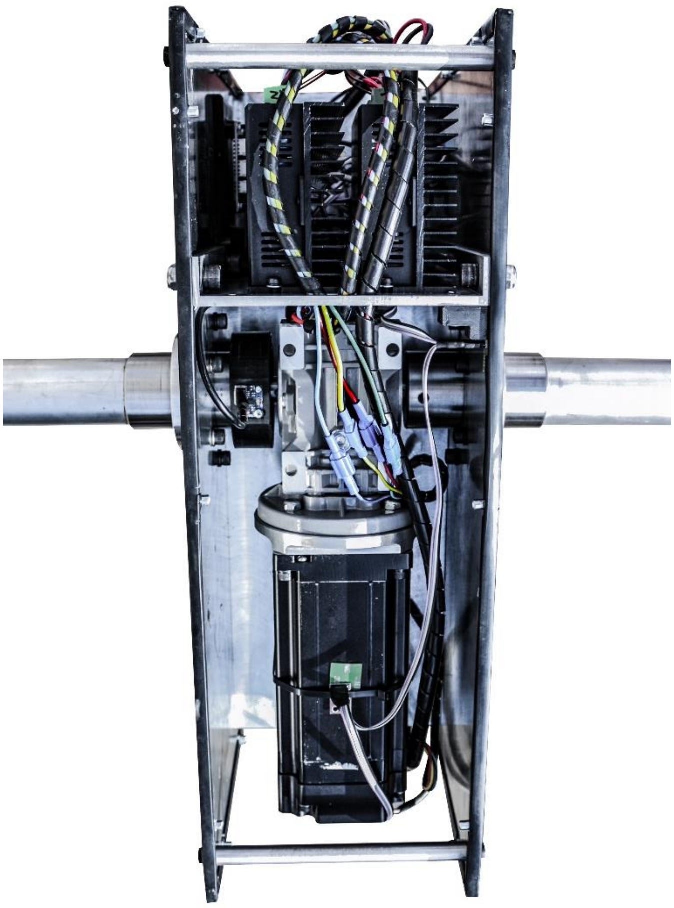


Figure 5 – ADA mechanical elements – Upper view

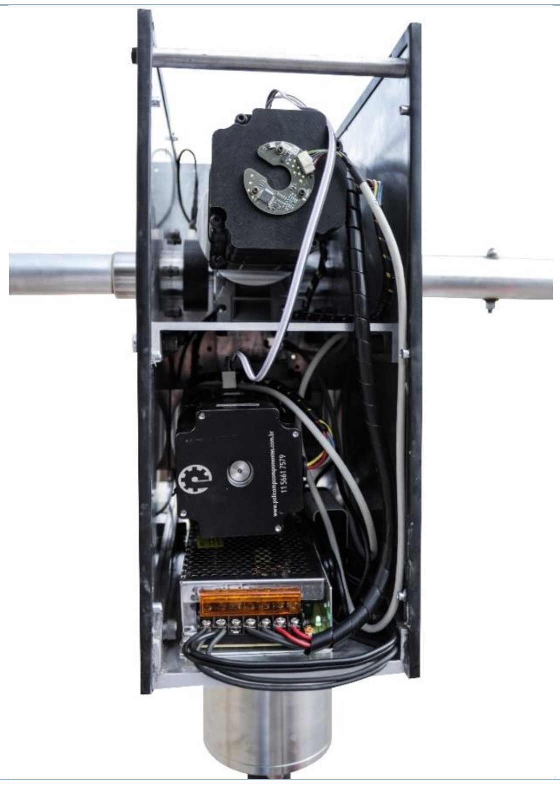


Figure 6 – ADA mechanical elements – Back view

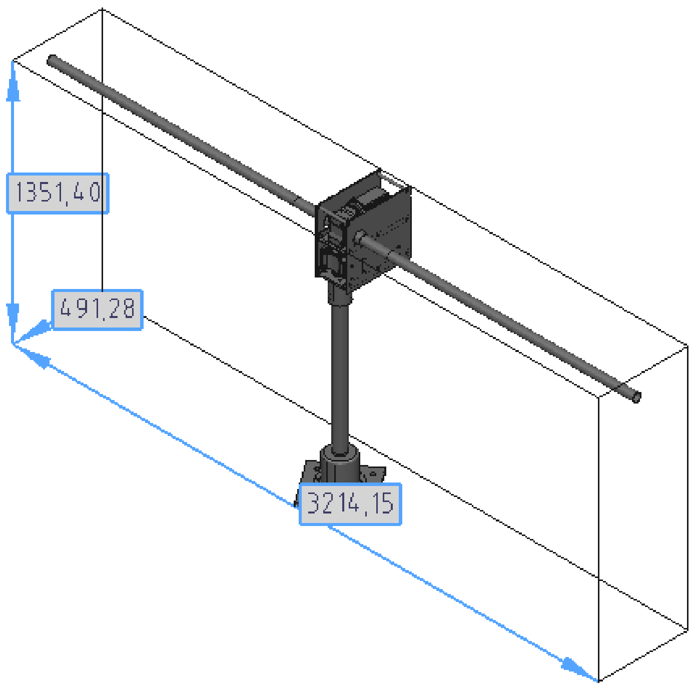


Figure 7 – ADA dimensions

2.3. ADASERVER: Satellite Tracking and Telemetry Software and ADA Control Software

ADASERVER constitutes proprietary software, written under the Linux operating system, which obtains the elevation and azimuth coordinates, calculates the Doppler Effect and sends them to the steering system (Controller), while also calculating the frequency based on the Doppler Effect and tunes the frequency of the SDR for command and reception of satellite signals, and their variations, or aerospace probe.

2.3.1. Orbital Trace Software

The satellite's position in space is obtained from its NORAD – North American Aerospace Defense Command – registration and made available via internet at www.celestrack.com address. The registration consists of a text file in the TLE – Two Lines Elements – pattern, which contains the orbital elements that define its position in space.

Given the initial position, it must be determined its orbit or passage forecast that is performed by PREDICT, which is an open-source, multi-user software and provides orbital forecasting and Doppler Effect in real time.

Thus, given the TLE, this is sent to predict that returns to ADASERVER the antenna pointing coordinates, that is, azimuth, elevation and Doppler displacement. ADASERVER sends azimuth and elevation to the Controller and, through Doppler Effect, adjusts the frequency of reception or transmission of the satellite that is used by the SDR.

2.3.2. Telemetry Data Acquisition Software

ADASERVER, upon the Doppler shift received, as described above, adjusts the satellite reception frequency by correcting the operation frequency, and thus receiving the signals. The SDR receiver delivers only the user's pre-selected radio frequency signal to the computer. Together with SDR, GQRX, that is open-source software and an SDR receiver developed based on GNU Radio and Qt Graphical Toolkit, are used to record the file in wave receiving format.

2.3.3. Command Software

ADASERVER controls the ADA sending/receipt commands, by initiating and ending tracking, allowing an observation schedule fully automatically, making corrections for the reception frequency as appropriate. Also writes/transmits the data collected file, sends commands to the orbited object directly (depending on the encoding of each object). After collecting data file received, it can be implemented post decoding processing. Sending/receiving complies with client/server principles, via TCP/IP, directly on the ADA IP, on a predefined port, with user/password authentication security, as well as data encryption.

2.3.4. Control Software

ADA can be operated automatically and remotely. For the control, a command line or TCP/IP interface was developed, which is interpreted and executed by ADASERVER. The main features involve updating TLE, data collection of the desired satellite, starting the capture service, among others. Below is the list of the main commands:

- **UPDATE**: Update TLE base;
- **DEF**: Set the satellite to be consulted and obtain its information;
- **FOLLOW**: Schedule signal capture of the defined satellite and consider its frequency and number of schedules;
- **DATA_COLLEC**: Collect data from azimuth, elevation and Doppler;
- **POS**: Send azimuth position and desired elevation to ADA Controller;
- **DOPPLER**: Calculate/apply frequency correction of the Doppler Effect;
- **START**: Start data file collection service, check the elevation for recording, and send data to the ADA controller, and finish recording;
- **V_REC**: Check the beginning and the end of file recording.

3. DATASAT - ADA GROUND STATIONS NETWORK

It is intended to stablish a ground stations network equipped with the ADA, configured as described in this document. The initial network will consist of ADA units installed in Brazilian and Portuguese territory such as Figure 8.

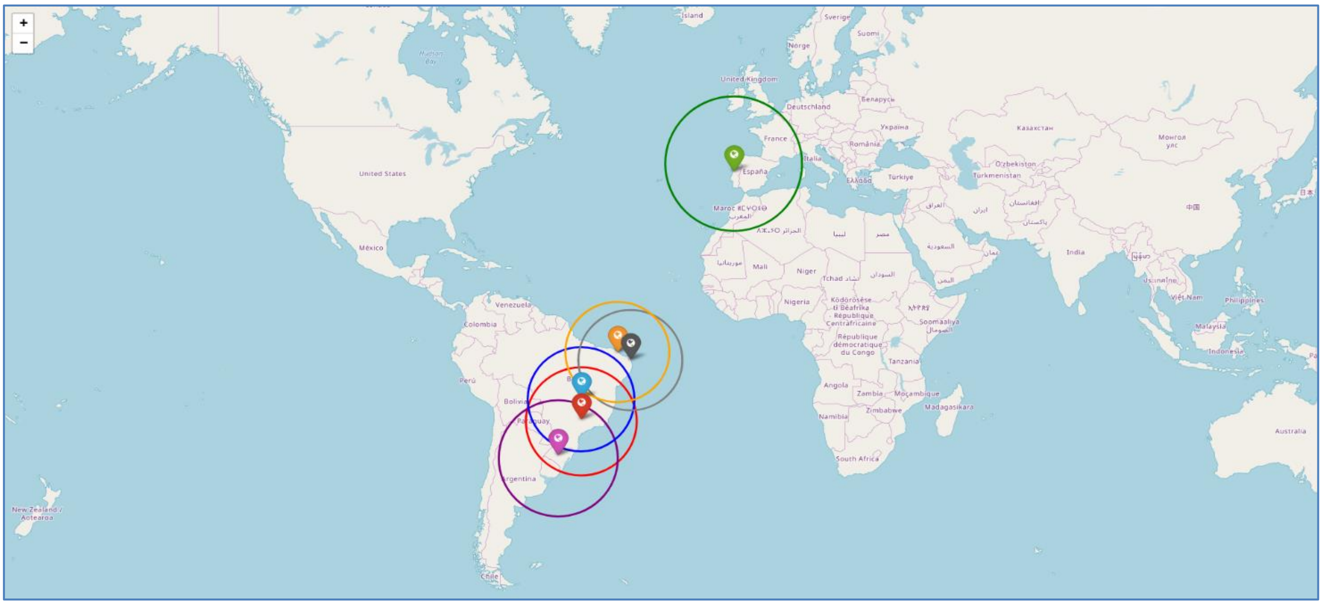


Figure 8 – Example of future facilities of ADA units

The objective is that ADA will be installed in cities and at research institutions based on partnerships formed with GRUPO CRIAR. The research institutions are those that have courses and disciplines related to aerospace engineering, aeronautical engineering, telecommunications, control and automation, radio communication, astronomy, astrophysics, among others.

In addition, the ground stations will be used in their Undergraduate and Graduate programs. At times when they are not being used by the courses, the GRUPO CRIAR will use their resources to capture or transmit signals to satellites that are in favorable orbit for the operation.

Currently four units are installed in Ribeirão Preto, SP and one installation in Portugal, capturing as an example, signals from satellites NOAA15, NOAA18, NOAA19 and ITASAT. The information collected is available on a webpage (http://datasat.space), as shown in Figure 9.

Satélite	Data/hora da passagem	Estação Terrena	Máxima Elevação	Ações
NOAA 18	2019-07-05 11:03:22 (UTC)	ET-CSS-001	43°	
NOAA 15	2019-07-05 10:22:40 (UTC)	ET-CSS-001	38°	
ITASAT	2019-07-05 10:12:48 (UTC)	ET-CSS-001	43°	
NOAA 19	2019-07-05 07:15:02 (UTC)	ET-CSS-001	38°	

Figure 9 – Registration of satellite tracking

Under "Ações" button, which means "Actions", it can be downloaded the original file or see its decoding according to Figure 10 and Figure 11.

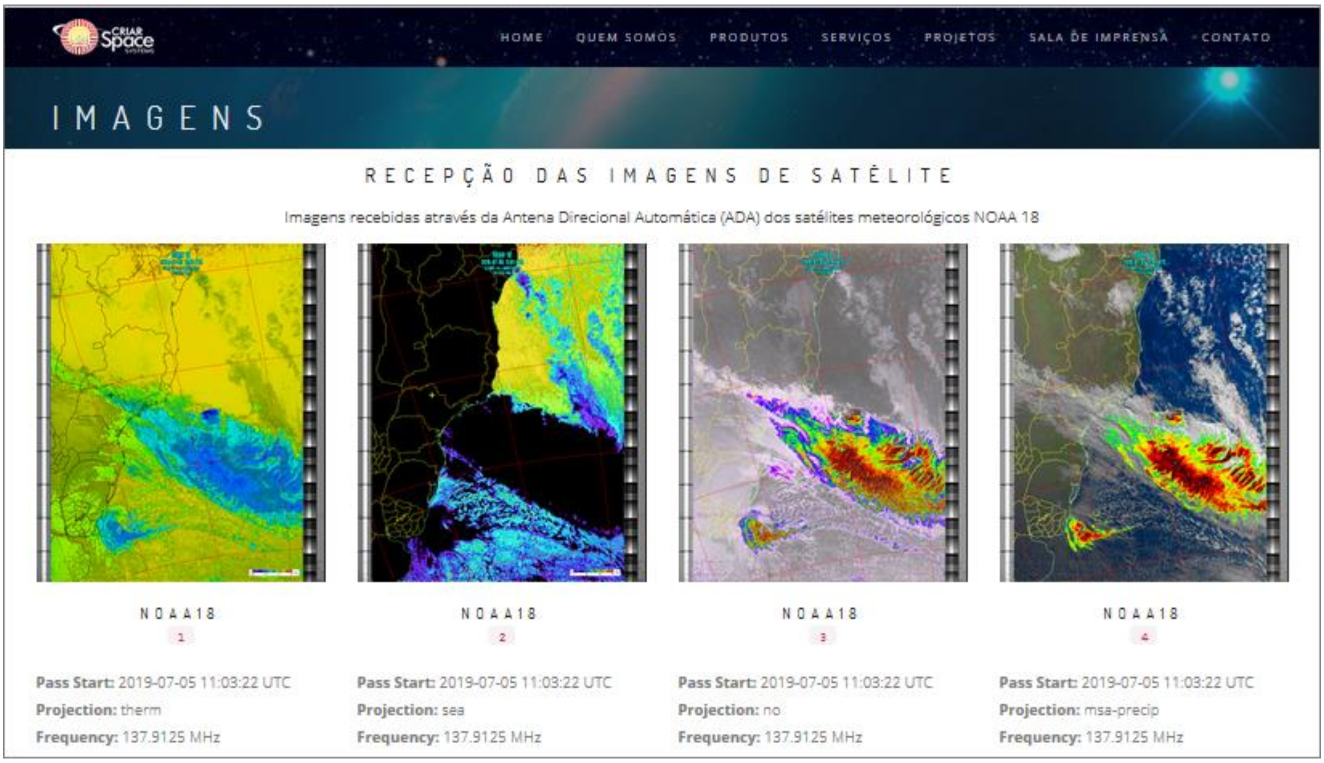
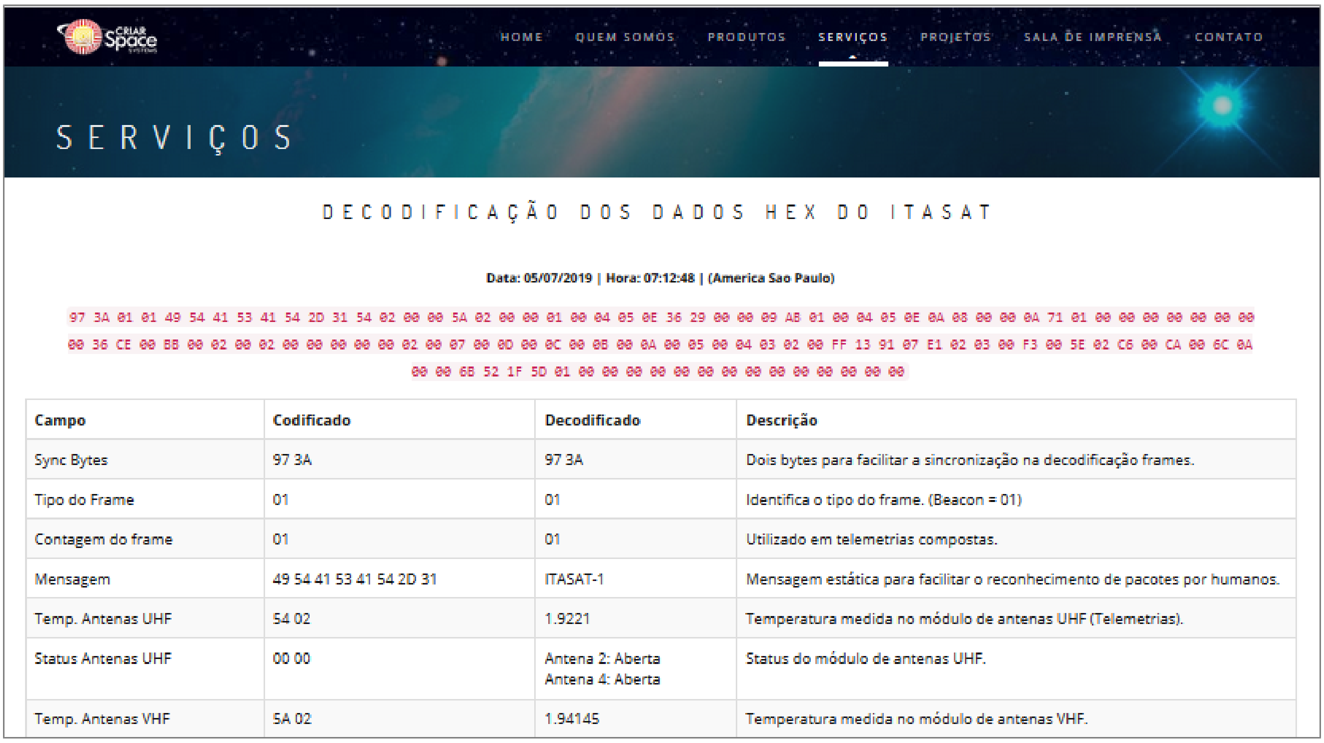


Figure 10 – Images of NOAAs satellites



DECODIFICAÇÃO DOS DADOS HEX DO ITASAT

Data: 05/07/2019 | Hora: 07:12:48 | (America Sao Paulo)

97 3A 01 01 49 54 41 53 41 54 2D 31 54 02 00 00 5A 02 00 00 01 00 04 05 0E 36 29 00 00 09 AB 01 00 04 05 0E 0A 08 00 00 0A 71 01 00 00 00 00 00 00 00
00 36 CE 00 BB 00 02 00 02 00 00 00 00 00 02 00 07 00 0D 00 0C 00 0B 00 0A 00 05 00 04 03 02 00 FF 13 91 07 E1 02 03 00 F3 00 5E 02 C6 00 CA 00 6C 0A
00 00 6B 52 1F 5D 01 00 00 00 00 00 00 00 00 00 00 00 00 00 00

Campo	Codificado	Decodificado	Descrição
Sync Bytes	97 3A	97 3A	Dois bytes para facilitar a sincronização na decodificação frames.
Tipo do Frame	01	01	Identifica o tipo do frame. (Beacon = 01)
Contagem do frame	01	01	Utilizado em telemetrias compostas.
Mensagem	49 54 41 53 41 54 2D 31	ITASAT-1	Mensagem estática para facilitar o reconhecimento de pacotes por humanos.
Temp. Antenas UHF	54 02	1.9221	Temperatura medida no módulo de antenas UHF (Telemetrias).
Status Antenas UHF	00 00	Antena 2: Aberta Antena 4: Aberta	Status do módulo de antenas UHF.
Temp. Antenas VHF	5A 02	1.94145	Temperatura medida no módulo de antenas VHF.

Figure 11 – ITASAT telemetry

4. CONCLUSIONS

With CubeSat satellites advent, an accessible, flexible and economical platform for scientific research, new technology demonstrations and advanced mission concepts, including satellite constellations, were provided. To keep up with this revolution and provide facilities for interested parties to interact with their satellites, there is a need for ground stations. The ground segment is as important as the space segment; however it is not the focus on itself of some research and missions. Thus, some projects provide services focused on ground segment and allow the monitoring of satellites.

ADA comes to meet the needs or requirements of a ground station with nanosatellite and microsatellite monitoring capability, as well as being low cost and with technology available on the national scenario avoiding long idle periods due to some repairs. A competitive product has been developed, which is available for various opportunities in research centers and educational institutions.

Moreover, considering that the average period of communication between the ground station and nanosatellite and microsatellites is restricted to minutes per day and that there may be other limiting factors for this communication, it is important to raise stations monitoring networks and preferably, that can be carried out remotely. In this way, the DATASAT network will provide this availability of communication through standardized and quality equipment, proving to be extremely important when one glimpses the size of the Brazilian national territory.

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