

A PROPOSAL FOR A SPACE WEATHER GROUND-BASED SEGMENT USING SOFTWARE-DEFINED RADIO AND COGNITIVE RADIO

Jaime E. Orduy⁽¹⁾, Walter. Dos Santos⁽²⁾, Claudia M. Cândido⁽³⁾, Douglas. Dos Santos⁽⁴⁾, Daniel S. Umaña⁽³⁾

⁽¹⁾National Institute of Space Research, 12227-010, +55 (12) 3208-6000,

jaime.orduy@inpe.br

⁽¹⁾Fundación Universitaria Los Libertadores, 111711, +57 (1) 2544750,

jaime.orduy@libertadores.edu.co

⁽²⁾ National Institute of Space Research, 12227-010, +55 (12) 3208-6000,

walter.abraham@inpe.br

⁽³⁾ National Institute of Space Research, 12227-010, +55 (12) 3208-6000,

claudia.candido@inpe.br

⁽⁴⁾ Aeronautics Institute of Technology, 12228900, +55 (12) 3208-6000,

dsoares@ita.br

Keywords: *Global Navigation Satellite System, Software-Defined Radio, Cognitive Radio, Space Weather, Public Outreach.*

The ionosphere is a highly dynamic medium through which radio waves propagate, but also the medium that interferes with this propagation. Due to there is a weakly ionized plasma located between around 60 km and 1000 km in altitude, formed by solar radiation mainly in the UV and X-Rays range, and which has high daily variability, as well as dependence on solar activity, the season of the year, and the geomagnetic activity, and others. The large-scale plasma depletions which develop from the geomagnetic equator are generally referred to as equatorial spread F, ESF, or Equatorial Plasma Bubbles, EPBs. EPBs are seen as large-scale depletions in TEC which leads to the fluctuation in the amplitude and phase of the radio wave signal that affects radio communication and navigation systems. In South America, Brazil has monitored the Ionospheric scintillation with relatively high-cost commercial instrumentation, by contrast, Colombia does not have a highly developed system to measure scintillation or even studies about the ionosphere. This paper aims to present the proposal on software-defined radio and cognitive radio techniques for space weather studies, in which the main objective is to propose a Space Weather Low-Cost Instruments Laboratory (SWLCL) for use in space weather studies and its implementation in a campaign at two points in the equatorial regions in the longitudinal sectors of Brazil and Colombia between October 2022 and March 2023, and October 2023 and March 2024 using the digital low-cost receiver RTL-SDR and Software Radio Peripheral USRP and opensource software toolkit for the software-defined radio GNU Radio to measure the TECs between the ground receivers and Low Earth Orbit Satellites (LEOS) [1] in order to implement the cognitive radio techniques as well, the scintillation algorithm method. Such studies include probes with ground-based receivers, introducing Cognitive Radio techniques in SDR-based technology for demonstrating how reductions in the development and implementation costs while replacing hardware components could draw near the space weather public outreach, as well as miniaturization processes for application as payload to CubeSats satellites. In addition to developing these capabilities for space research, it is intended to study the feasibility of their applications in the area of accident and disaster prevention, as well as in the area of air defense and telecommunications, all of the technological, strategic, and social interest.

1. Introduction

In the Brazilian sector, where the magnetic equator presents a remarkable negative declination angle at $\sim 20^\circ$, the climatology of EPBs is well-known, with peaks at equinoxes and December solstice. The climatology of scintillation follows the EPBs, and there are differences between distinct longitudinal sectors, which depend on local times and other factors. As mentioned previously, there is a lack of detailed information on EPBs and scintillation over Colombia, although this is of great interest for navigation and aeronautics. Scintillation processes affect the radio waves propagation in the ionosphere, which can be degraded in situations where the ionosphere is disturbed or presenting irregularities, see reducing the quality of the signal, errors in the positioning, or even loss of locking of the radio signal traveling between satellites that make up the navigation and positioning systems, such as the constellation of Global Navigation Satellite Systems, GNSS, satellites. Figure 1 represents the radio wave passing through a region with plasma irregularities (blue dots) before arriving at a ground-based receiver.



Figure 1: Radio wave through the disturbed ionosphere [2]

The process that degrades radio signals, well-known as Ionospheric scintillation, consists of fluctuations in the amplitude and phase of radio signals associated with EPB interferences. EPBs develop around post-sunset at the geomagnetic equator, move vertically and propagate simultaneously eastward and toward higher latitudes by diffusion, pressure gradient, and gravity. Therefore, an Ionospheric flicker can cause phase errors, ambiguity due to the number of cycles, increased carrier wave Doppler instability, or signal losses, which can induce errors of tens of meters or complete signal interruption. Worth mentioning that typically, the lower L band frequencies are more affected than, the higher frequencies indicating the focus of the thesis and the problem to be solved [3].

EPBs originating in the equatorial region can drastically interfere with the propagation of radio signals between satellites and ground receivers, especially in the regions where the plasma gradients are stronger, i.e., around the crests of the Equatorial Ionization Anomaly, EIA, which consists of two density crests around approximately 15 degrees of latitude north and south of the geomagnetic equator. In Brazil, one of the ionization crests is at approximately 23° S (geographic latitude). In Colombia, the north crest is around Bogota (Mag Latitude: 13.93° N). Additionally, scintillation can be strengthened or suppressed during geomagnetic activity associated

with Space Weather events. Figure 2. shows the dependency of the S4 with solar activity for two solar cycles from 1998 to 2014 [4].

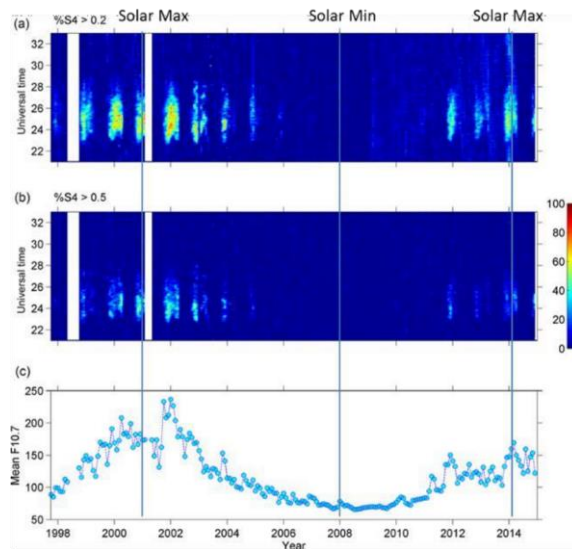


Figure 2: S4 with solar activity for two solar cycles [4]

The Ionospheric scintillation is monitored throughout the Brazilian territory, with relatively high-cost commercial instrumentation, as indicated in [5] and states the need for more complex logistics for data handling. On the other hand, in Colombia according to Ionospheric Irregularities are measured using Ground-Based GPS Networks [6]. Figure 3 show the Low-Latitude Ionospheric Sensor Network, LISN, over Latin America.

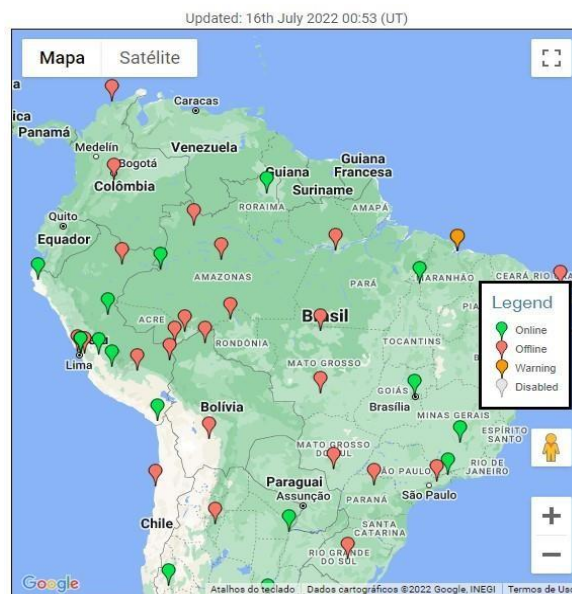


Figure 3: Low-Latitude Ionospheric Sensor Network – 2022 [7]

In this regard, the concept of Software-Defined Radio applied to Ionospheric monitoring and telecommunications technological decisions are of great interest because it can mitigate the operational difficulties of remote monitoring systems. The objective of using SDR in Ionospheric continuous sounding geomagnetically quiet periods and during space weather events has the advantage of providing higher

coverage in terms of applications in the space area, using the constellation of GNSS (Global Navigation Satellite Systems) satellites and Geostationary satellites for VHF-bands. Such applications include high configurable and flexible probes with ground-based receivers. Furthermore, the SDR concept has good potential for miniaturization and application as a payload in CubeSats satellites, in addition to developing these capabilities for space research. Mitolla apud Albayrak defines Cognitive radio as an agent as software that exhibits the functional attributes of autonomy, interactivity, reactivity, goal-orientation, mobility, adaptivity; and that is capable of planning, reflection, and cooperation [8]. Besides, points out that cognitive refers to the mix of declarative and procedural knowledge in a self-aware learning system [8].

The CR inclusion is the highlight of the proposal. Bakare and Okolie declare that Cognitive Radios are intelligent devices with the ability to sense environmental conditions and can change their parameters according to the requirements to get the optimized performance at the individual nodes or the network level [9]. Thus, CR is widely regarded as one of the most promising technologies for future wireless communications, including Improve satellite communications. But, perhaps, there is no complete automation, and it requires user intervention for any changes to be implemented. It is thought to include machine learning to generate complete automation for the ground station to manage this disadvantage, and add, Adaptive Radio in which communications systems have a means of monitoring their performance and varying their parameters by closed-loop action to improve their performance. Finally, the hypothesis is that incorporating CR into SDR adds greater flexibility in handling Space weather research and monitoring. Therefore, based on the above problem, this work proposes the Software Defined Radio (SDR) platform development using a Cognitive Radio approach to simulate and replace the degraded signal-associated errors to monitor the Equatorial Plasma Bubbles having ground stations receiving signals.

3. Methodology

In this session, it is presented the general methodology and strategies to develop capabilities on detection, monitoring, prediction, warning, and decision making using cognitive radio. From the point of view of the approach to the problem, it will implement two methodologies. On the other hand, to implement the CR algorithms and techniques in the SDR, the methodology adopted is the Design Science Research Methodology (DSRM) is adopted; according to Von Brocke et al., it is a problem-solving paradigm that seeks to enhance human knowledge by creating innovative artifacts [10]. Conforming to Peffers et al., a six-step Design Science Research Methodology will be used, and the results will be published as scientific literature, as shown in Table 1 [11].

Table 1. Design Science Research Methodology

Research Step	Concerns	Output Next Step	to	Entry Point?	Thesis stage methodology design
1. Identify Problem & Motivate	Define problem & Show importance	Inference		ProblemCentered Initiation	Explore academic publications.
2. Objectives of Solution	Define What would a better artifact accomplish?	Theory		Objective Centred Initiation	Define the algorithms for ionospheric scintillation detection and validation of the s4 index measurements
3. Design & Development	Artifact	How-to Knowledge		Design & Development Centred Initiation	Define the needs, requirements, and constrains of the laboratory. Modelling the ground station receiver based on the machine learning and cognitive radio techniques.
4. Demonstration	Find suitable context Use artefact to solve the problem	Metrics, Analysis Knowledge		Client/Context Initiated	Detect and monitoring of the ionospheric scintillation occurrence process in a case study.
5. Evaluation	Observe how effective, efficient Iterate back to design	Disciplinary Knowledge			Write the document.
6. Communication	Scholarly publications Professional publications				Present the results.

Source: Adapted from [11]

3.1. Hardware Proposed Prototype Development

The scintillation processes of the interest in navigation, positioning, and aeronautics occur in L-band frequencies: L1 (1575.42 MHz); L2 (1381.05 MHz), and L5 (1176.45 MHz) with more emphasis in the L1-band. VHF-band is of interest for monitoring and for strategic defense systems and will be considered as one of the modes of sounding. It is expected to construct an SDR prototype adding the CR techniques to mitigate the effects of the noise and errors caused by ionospheric scintillation and ensure the quality of the satellite signal by avoiding fading into the EPB. It should be noted that the mastery of such techniques with ground receivers has the potential for miniaturization processes and application as a payload in CubeSat satellites. The proposed prototype includes two stages.

The first stage defines low-cost commercial hardware: a handmade eggbeater antenna (300 MHz and 3-GHz beacon) and an RTL-SDR dongle. This stage encloses

the scintillation detection and monitoring during observations, validation by comparison with conventional systems, and implementation of models over the GNU and cognitive radio plugins. It is worth mentioning that the stage in hardware is already built and installed at Bogota, Colombia in the Solar Radiometry Laboratory at Fundación Universitaria Los Libertadores, as shown in Figure 4.



Figure 4: Proposed prototype topology

The coordinates of the station are shown in Table 2

Table 2: Implemented prototype first location

Fundación Universitaria Los Libertadores Solar Radiometry Laboratory		
	Geographic	Geomagnetic (2022)
Latitude:	4°39'6.17"N	13.93N
Longitude:	74°35'6.89" W	1.97W
Altitude	2579 M.S.N.	

This location was chosen due to it is a desire to improve the Solar Radiometry Laboratory. By 2022, this laboratory has a meteorological monitoring station and a radiometry station; with this improvement, it is predicted the consolidation of a scintillation low-cost monitoring system in Colombia. The second location was chosen due to the proximity to INPE, where conventional receivers are in operation for validation, and the possibility of using some of the facilities at the Electronic Engineering Division at ITA in Sao José dos Campos – Sao Paulo, Brazil, as shown in Table 3.

Table 3: Proposed prototype second location

Instituto Tecnológico de Aeronáutica (ITA)		
	Geographic	Geomagnetic (2022)
Latitude:	23°12'33"S	14.70S
Longitude:	45°52'30"W	25.39E
Altitude	597 M.S.N.	

Additionally, the use of other commercial hardware, such as Raspberry PI4, in developing the first models of the laboratory is considered to create a reliable system and to configure a portable ground station; Figure 5 establish the topology of the system; here, the software is the one that has to be developed.

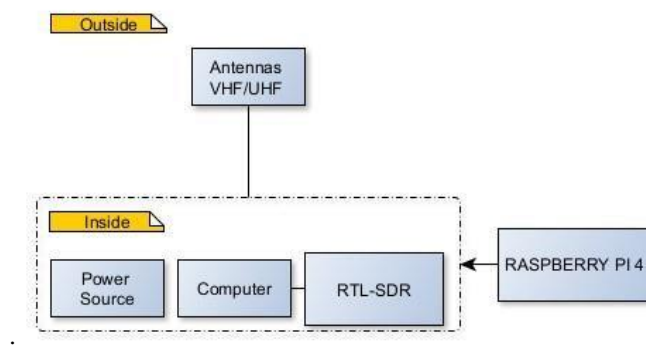


Figure 5: First stage topology

The second stage of the hardware proposed prototype integrates into the first model (first stage) the use of a more robust component in hardware, a USRP N210, see Figure 6 to provide more frequencies and better reliability. The ground station will be oriented by the model of [1].



Figure 6. Second stage major component in hardware
Source: [12]

According to Yamamoto GNU Radio is based on the script language Python; it is also possible to expand the capabilities of the GNU Radio by adding more signal processing codes in C++ [1].

3.2. Software Proposed Prototype Development

As mentioned previously, Cognitive Radio is a generic term used to describe a radio that is aware of its environment and can adapt its transmissions according to the interference it sees. The use of CR in this work is proposed to include an intelligence model over the GNU radio to the whole system. On the other hand, GNU Radio is the open-source software toolkit for the software-defined radio over the Linux Operating System selected to create the software prototype completely reconfigurable. In this way. It is intended to include the CR to identify the scintillation effects on radio signal propagation and over SDR software to mitigate, correct, and compensate. Figure 7 shows the functional diagram for the RTL_SDR, which has by "default" the frequency of the ATIS (Automatic Terminal Information Service) available at São José dos Campos International Airport as a use example. The Null Sink block is a simplified representation of the solution implementation for Cognitive Radio in this work. For the

prototype, it will be necessary to initially specify the variables and constants that will compose this solution before starting the implementation of the block. In this way, expanding and describing the variables and constants in the final work is mandatory.

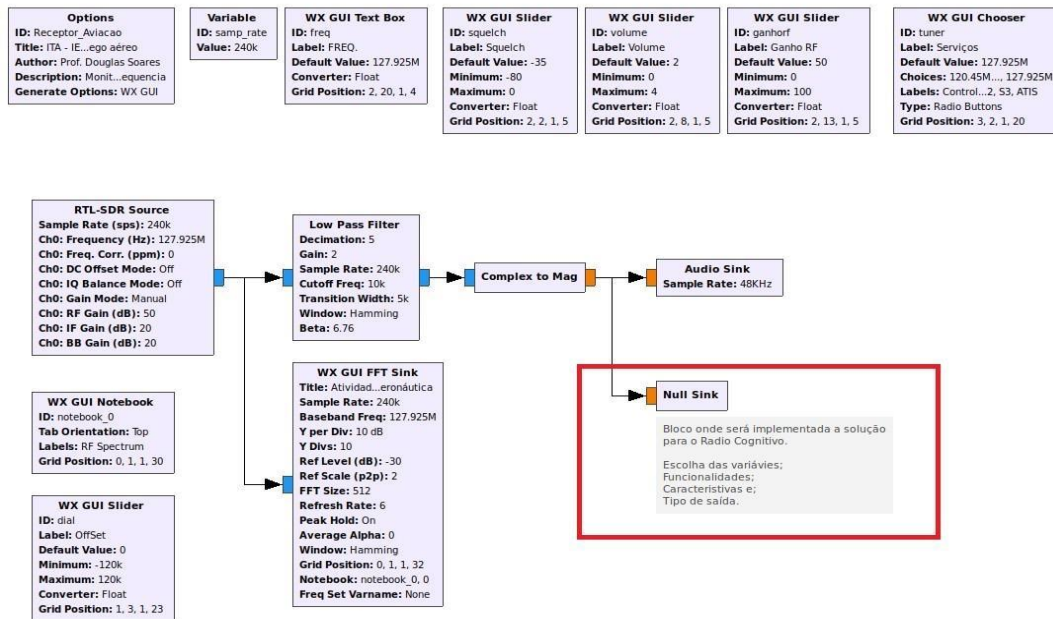


Figure 7. Implementation for Cognitive Radio

According to Biglieri, using Software-Defined Radios and Cognitive-radio protocols allows greater flexibility for new standards and concepts [13]. For example, using software radio, the devices generating multiple antenna beams can create the necessary number of beams with adjustable position and size or adapt their transmission parameters to adjust to the current propagation conditions. Narayan and Chandrasekharan in Biglieri affirm that the bands below 3.5 GHz have lower propagation loss and are sought after by all services. For this reason, one of the frequencies chosen in this document was the L-Band and VHF or even UHF [14].

4. Results

The proposal aims to generate knowledge whose central theme concerns the Cognitive Radio applied to the SDR approach to determine and mitigate the scintillation effects of navigation satellites' signals. It is expected to obtain an SDR monitoring system with high flexibility, reconfigurability, accessibility, and applicability in space weather that can monitor the Ionospheric scintillation in the L-bands and VHF bands using a case study carried out in two different areas, Brazil, and Colombia. Taking advantage of SDR represents an innovative low-cost, and flexible platform for multipath error studies, Ionospheric scintillation analysis, and, above all, GNSS reflectometry test and development. It is desired that the development of the Cognitive Radio algorithm, the design of the communication system, and its formalization in a SE process provide a proposal to be applied in mitigating the effects of scintillation in the reception of navigation and telecommunication satellites.

The main objective of the proposal is to develop a Scintillation Low-Cost Monitor System Laboratory (SLCL) based on the concept of Software-Defined Radio (SDR) for detection, monitoring, and warnings of the occurrence of Equatorial Plasma Bubbles

(EPB), as well as the Ionospheric scintillation. For this purpose, it is considered the technique of Radio Cognitive algorithms using the L-band signals (L1S: 1575.42 MHz) of the constellation of Global Navigation Satellite Systems satellites, GNSS, and VHF geostationary satellites (30 MHz to 300 MHz) available.

In order to complete the objective of the proposal: It is expected that the development of the system will agree to programmatic and regulatory restrictions, verification of the needs of the stakeholders, integration work, modeling program, simulation, and testing in order to provide a design; the simulation results on GNU RADIO will demonstrate the feasibility of using Cognitive Radio algorithms for application in problems such as the scenario presented; A campaign will demonstrate the utility of the (SWLCL) in the case study with two points over the geomagnetic equator. Bogotá, Colombia (North Latitude: 4°35'56" and West Longitude of Greenwich: 74°04'51") by the north side and Sao José dos Campos, Brazil, (Latitude: South, 23° 12' 33", Longitude: 45° 52' 30" West); and finally, It is expected that the system developed could aid in demonstrating its usability in the design of the multi-band communication system to monitor, detect and warn EPB and Ionospheric scintillation related to space weather.

5. Discussion

A simultaneous observation campaign in the longitudinal sectors of Brazil and Colombia will be implemented between December 2022 and March 2023 and between October 2023 and March 2024. The technology involves low-cost SDR digital receivers and the open-source software GNU Radio to measure scintillation between ground stations and GNSS satellites. Include probes with ground stations introducing machine learning and Cognitive Radio techniques into SDR-based technology to demonstrate how reductions in the development cost while replacing hardware components could draw near the space weather public outreach and could generate a new way to measure scintillation while it is learning about the ionosphere, and it is optimizing the communications channels between the ground stations and the satellites. Figure 8 shows the project purpose in general.

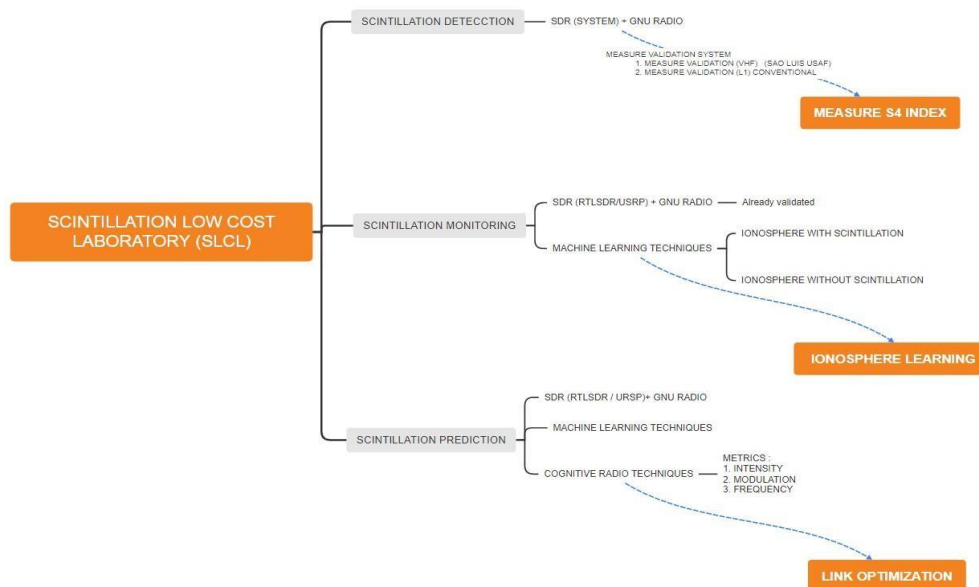


Figure 8. Project purpose in general

In fact, according to Abdu et al., in 2002, a campaign called COPEX was conducted during the October–December 2002 period in Brazil to investigate the equatorial spread F/plasma bubble irregularity (ESF) development conditions in terms of the electrodynamic state of the ionosphere along the magnetic flux tubes in which they occur [5]. In this way, it is desired to implement a similar campaign to investigate the equatorial spread F/plasma bubble irregularity over two distant and different points referenced by the geomagnetic equator with another cheaper and more flexible technology.

Acknowledgments

The authors would like to thank the National Institute for Space Research and the Fundación Universitaria Los Libertadores for their generous support and encouragement during the preparation of this manuscript.

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