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Protection of Earth Observation Satellites From Radio-Frequency Interference

Policies and practices

Carrying onboard remote sensing systems, Earth observation (EO) satellites provide unique global, systematic, and consistent space-based measurements of natural and man-made phenomena. Measurements can be produced on atmospheric, surface, and subsurface characteristics, properties, and constituents as well as other indicators and related data, enabling comparisons in time and across different parts of the globe, including remote and otherwise inaccessible areas.

The range of applications for those observations is wide, addressing private endeavors as well as all sectors of public policy and decision making, with an obvious key multisectoral direct impact widely described in the literature [1], [2], [3], [4], [5], [6]. In particular, EO missions providing services based on remote sensing data become ever more relevant for global governance, with examples related to pressing societal challenges going beyond the borders of individual countries and requiring a global response to weather and energy forecasting [7], environmental and climatic monitoring [8], [9], economic security hazard detection [10], and situational awareness for heritage conservation [11], [12] and crisis management (including efforts of a humanitarian nature) [13], among many others.

EO-driven services, however, may be impaired by radio-frequency interference (RFI), the mitigation of which is essential to restore data integrity and the associated quality of service. Hence, maximizing the return on investment on deployed spaceborne infrastructure is contingent of RFI management [14], [15]. Albeit possible and routinely carried out, RFI mitigation is limited by the lack of regulatory evidence because RFI cases remain largely unreported; what is not reported is assumed not to exist. It is thus important to understand the regulatory outline of RFI and radio protection as well as the procedures for claiming the second and the methods for mitigating the first.

In this contribution, the subject of radio protection is addressed from the perspective of a national administration responsible for regulating, providing access to, and supervising RF spectrum resources (hereafter referred to simply as *spectrum*) under its jurisdiction and used by EO missions. The case in point is the experience of Portugal, given from the perspective of its institutional framework.

THE MEANING OF BEING AN ADMINISTRATION

In Portugal, the administration is the Autoridade Nacional de Comunicações (ANACOM), established in 1989 as the national regulatory authority for communications. Its scope includes both electronic and postal communications. Since 2019, it has also served as the space authority in Portugal. In the area of electronic communications, ANACOM is responsible for the management of the numbering resources; market regulation and surveillance; infrastructure regulation and supervision; security of communications and emergency communications; coordination among civilian, military, and paramilitary uses of radiocommunications; and ensuring the efficient and effective management of scarce natural spectrum resources, which are the essential physical assets enabling all radiocommunication services, which the so-called science services are examples of [16]. In this sense, ANACOM's role and actuation are geared by principles of independency, including in terms of its technical capabilities as well as by values of transparency, equity, and proportionality, ensuring impartiality and establishing priorities in the spirit of the International Telecommunication Union (ITU) Radio Regulations (RRs) [17].

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EARTH OBSERVATION AS A RADIOCOMMUNICATION SERVICE

RADIOCOMMUNICATION SERVICES RELEVANT TO EARTH OBSERVATION

From the regulatory point of view, EO satellites carry onboard space stations, defined in the ITU RRs as "one or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary … for carrying on a *radiocommunication service*" [17]. These stations are located on an object that is going, is intended to go, or has been beyond the major portion of Earth's atmosphere.

Among the different radiocommunication services relevant to EO, perhaps the most obvious is the Earth exploration satellite service (EESS), formally defined in article 1 of the RRs and briefly summarized in the scope of this contribution as "a *radiocommunication service* between *Earth stations* and one or more *space stations*, which may include links between *space stations*, in which information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment, is obtained from *active sensors* or *passive sensors* on *Earth satellites*." Other services relevant to EO include, for instance, the meteorological satellite service (MetSat), which is an EESS for meteorological purposes, and the meteorological aids service.

RADIO-FREQUENCY ALLOCATIONS

Together, the referenced radiocommunication services have frequency allocations ranging from 8.3 kHz to 252 GHz as well as frequency identifications well beyond that, detailed in article 5 of the RRs in the so-called Table of Frequency Allocations (TFA). The rank of priorities for using a given frequency band in the TFA is established by defining primary and secondary radiocommunication services, with the first ranking in higher priority with respect to the second, in which stations can claim protection only from other stations in secondary services, whose frequencies have been assigned at a later date.

The frequency allocations used by EO missions may be generally categorized according to their application, particularly for communications and measurements. The first includes the reception of telemetry, space tracking, transmission of commands to the platform, and payload data transmission, containing the desired data justifying the mission in the first place, to designated gateway Earth stations and directly to service users' Earth stations [18]. The second includes active and passive sensing of Earth, and, contrary to what happens with communication links whose spectrum requirements are driven by engineering factors, its spectrum requirements are naturally defined by the laws of nature [14]. Given their unique character, it is not surprising, then, that some of these, in particular, some for passive sensing, require ultimate radio protection. In this sense, frequency allocations for measurements may be further categorized according to their sharing scenario with other systems as shared with active services and as shared with passive services (only), i.e., subject to RR 5.340, stating that "all emissions are prohibited" in these bands. A summary of the frequency allocations to EESS and MetSat and relevant applications enabled by these services is displayed in Figure 1. The service designation is listed on the left, and its applications are on the right-hand side of the figure.

FOR PREVENTIVE RADIO PROTECTION, SPECTRUM AUTHORITY OFFICERS CONDUCT FREQUENT INSPECTION ACTIONS ON STATIONS OF DIFFERENT RADIOCOMMUNICATION SERVICES UNDER THEIR JURISDICTION.

RADIO LICENSING AND SPECTRUM ACCESS

Space stations in the EESS and MetSat of other administrations are not subject to any form of radio licensing and registration in Portugal. Their conforming frequency assignments are expected, nonetheless, to have been duly notified to the ITU and recorded in the Master International Frequency Register. The respective transceiver Earth stations, in turn, are subject to radio licensing as well as receiver-only Earth stations operating in primary frequency bands for which protection against harmful interference has been required. The licensing of receiving-only Earth stations is not mandatory, and, although there is no entitlement to formal radio protection, such stations may not necessarily operate in any RFI environment. This will be detailed further.

RADIO PROTECTION AND SPECTRUM SUPERVISION IN EARTH OBSERVATION

RADIO PROTECTION: DEFINITION AND INFRASTRUCTURE

By establishing a fundamental common ground for understanding, the ITU provides international recognition and protection of the rights of its member states (MSs) to access and use spectrum and satellite orbits, governing them at the international level with the objective to ensure such access and use to be effective (RFI-free), rational, equitable, efficient, and economical, which is particularly important given the resources' natural scarcity. For this, the ITU RRs are the leading international radio regulatory instrument, providing a stable planning environment for administrations, manufacturers, operators, users, and other stakeholders. Being part of the ITU administrative regulations and instruments, the RRs contain provisions of a technical nature governing international telecommunications, and they complement the provisions of the ITU constitution (CS) and convention (CV) defining the ITU purpose and structure. These are legal intergovernmental treaties, binding to all signatory MSs, who must apply their provisions in their countries by force of law.

Radio protection may be defined as a set of actions securing compliance in using spectrum. This is afforded by administrations, having sovereign jurisdiction over such spectrum, to stations with a recognized right, and it stems from national legislation that includes the provisions of the ITU CS and CV and RRs. Radio protection may be categorized in two strands: preventive and reactive. Whereas the first aims to avoid harmful interference, the second aims to solve harmful interference cases that could not be prevented. To afford radio protection, administrations rely on a number of key legal and technical instruments to conduct investigations and enforce required conformity. These instruments largely determine their range of action.

To ensure the most effective and efficient management and usage of spectrum, ANACOM has continuously invested in its monitoring facilities. In particular, ANACOM has four spectrum monitoring and control (SMC) centers, located in Barcarena (near Lisboa), Funchal (Madeira), Ponta Delgada (Azores), and Porto (see Figure 2), which are complemented by 22 fixed SMC remote stations deployed across the country (Figure 3). This fixed infrastructure is fundamental in providing the first intelligence for action, regardless of its preventive or reactive nature, and in supporting and guiding actions in the field, which may be carried out by SMC mobile stations (Figure 4) as well as by portable SMC stations whenever and wherever needed. Finally, existing fixed infrastructure may be further extended by transportable SMC stations that may be deployed in specific campaigns. All these instruments are used in both strands of radio protection, which is provided by a spectrum monitoring and enforcement service running permanently, 24 h a day, every day. Finally, ANACOM has been engaged in the continued development of the ITU International Monitoring System [19], actively participating in it. The list and characteristics of the participating stations are in [20].

PROCEDURES IN CLAIMING AND METHODS IN PROVIDING RADIO PROTECTION

For preventive radio protection, spectrum authority officers conduct frequent inspection actions on stations of different radiocommunication services under their jurisdiction, regardless of their location (on land, on the sea, and in the air) and based on a proportional, objective, and nondiscriminatory approach to preserve the market competition among operators of the same service and among operators of different competing services. The objective is to secure their rights and enforce their obligations by checking and enforcing compliance with the applicable legal and regulatory framework and their admissible technical characteristics and established operational conditions.

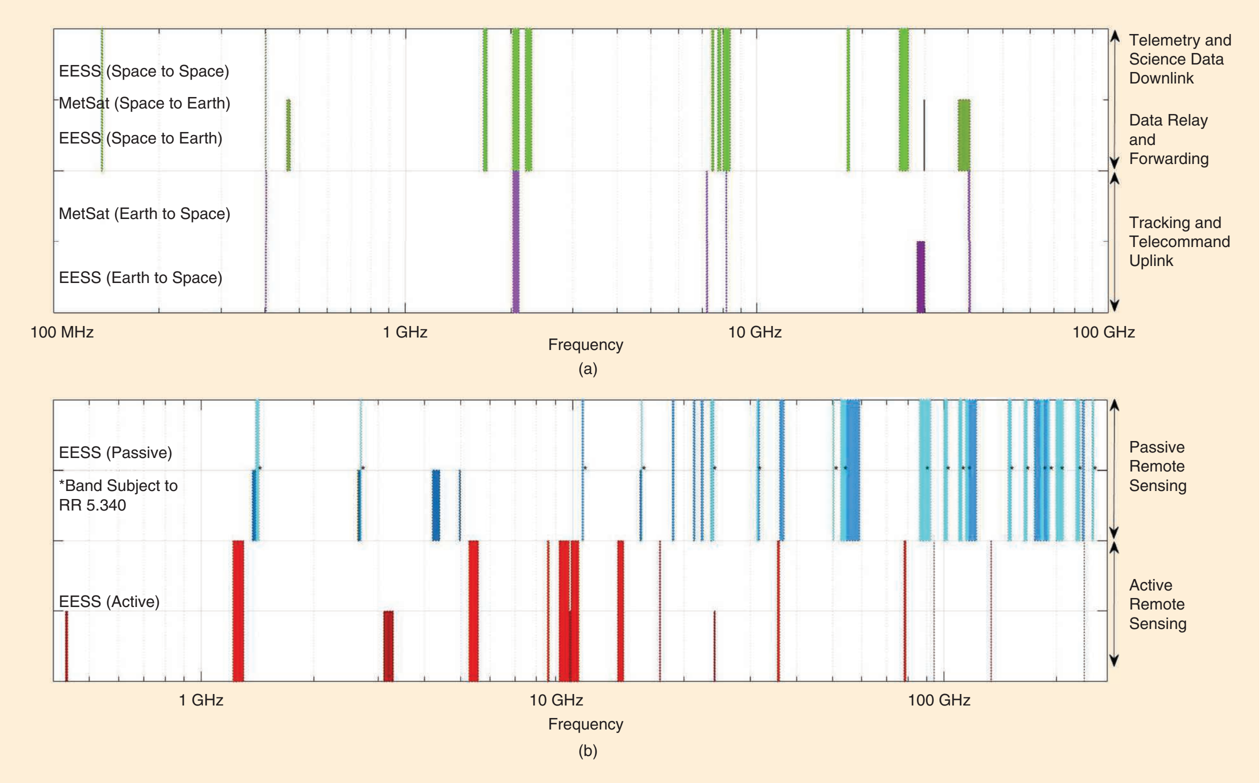


FIGURE 1. Frequency allocations to EESS and MetSat services and respective applications: (a) EESS/MetSat frequency allocations for communications and (b) EESS/MetSat frequency allocations for sensing. Allocations represented by thicker stripes indicate bands where the corresponding service is primary, whereas thinner stripes of the same but darker color indicate allocations where the respective service is secondary.

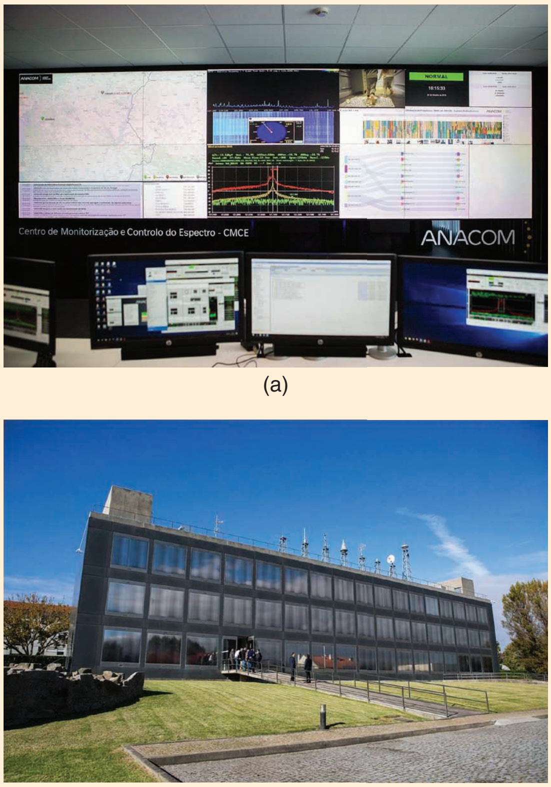
Furthermore, intentional unauthorized uses, unintentional uses resulting from faulty equipment, and other noncompliant uses and electrical and electromagnetic phenomena may compromise the radio spectrum. For these, spectrum authority officers also conduct preventive spectrum monitoring actions in the field to assess actual statuses and secure the natural integrity of spectrum resources, including those that may remain unassigned to keep them readily available for use by future systems. This assessment is particularly important in the framework of preparatory activities for the deployment of emerging technologies. The preventive practices described previously are the result of so-called spectrum monitoring and enforcement plans, which aim to effectively and efficiently monitor and control spectrum and preventively inspect radiocommunication services and associated stations and networks in accordance with the administration policy.

Spectrum monitoring actions are equally important in detecting RFI cases that have not been reported yet. The reasons for such RFI to have not been reported may vary, but that does not mean that the interference is not of a harmful character. Actually, this strand of radio protection, together with important advances recently achieved to enable further pushing the boundaries of RFI detection [21], may play an essential role in detecting low levels of harmful interference, which is particularly critical to passive sensors onboard of EO missions, considering their difficulty (if not inability) in distinguishing between man-made and natural emissions, and in reporting them before it is too late to act [22], [23]. The risk is for this insidious RFI to fall initially within the plausible range for measurement values, leading, by the time the interference level becomes detectable (and reportable), to the data provided by the relevant compromised services, including those of environmental monitoring and meteorological prediction, being widely accepted, recorded, and used for different applications enabled by those services, potentially resulting in the provision of faulty evidence, erroneous weather forecasts, and false severe weather warnings, with negative social and economic consequences, including on public safety and on property protection.

Notwithstanding preventive practices, unforeseen situations are treated by reactive practices through the mobilization of teams for intervention in the field. It is ANACOM policy that reactive radio protection is afforded whenever necessary and possible. For that, all that is needed is a report of an apparent anomaly, which may be submitted by any appropriate direct or indirect communication channel, including the ITU Satellite Interference Reporting and Resolution System (SIRRS) [24]. As a baseline, the utmost goodwill is exercised in cooperating and assisting with solving any difficulty and anomaly, regardless of any procedural particulars. Nonetheless, the procedural provisions of article 15 of the RRs must be followed (including sections 15.27 [25], [26] and 15.30) and, for the particular case of passive sensors operating in the framework of the EESS [27] should also be considered. There is no similar recommendation for the case of active sensors.

Facing a claim for radio protection, spectrum monitoring and enforcement reactive actions are triggered with the objective to duly probe the case and provide an appropriate response to the reported anomaly. This practice is applied regardless of the source of the report (users, operators, other administrations, and so on) and the regulatory recognition of the station and its apparent entitlement to radio protection. In this initial phase, it will be too soon to provide a statement regarding the cause of the apparent anomaly, including whether the origin is in an interference case or not and if so, which recognized nature (permissible, accepted, or harmful) it possesses.

Priority will be given to critical safety services used for the safeguarding of human life and property and whose failure may cause eminent danger to life and infrastructure. Specific examples include aeronautical and maritime mobile as well as radionavigation services. Other requests will be treated on a first-come, first-served basis. In properly ranking cases affecting EO missions, it is important to consider that a particular RFI affecting an EESS or MetSat affects the weather and climate services provision not only over the region directly affected but also worldwide and



(a)

(b)

FIGURE 2. ANACOM's SMC center in Porto, Portugal. (a) Spectrum monitoring and control room. (b) Main building of ANACOM Delegation in Porto.

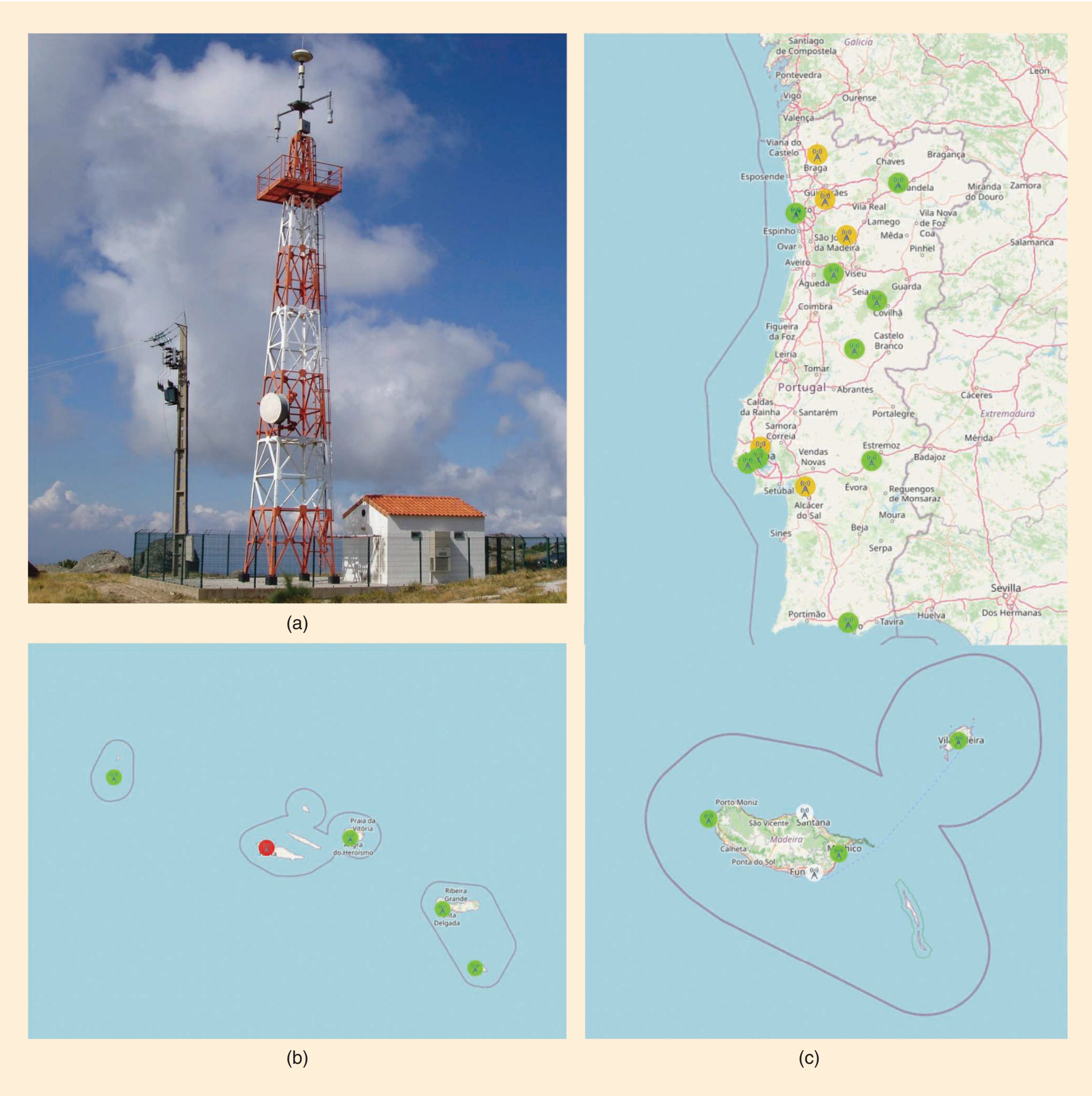


FIGURE 3. (a) SMC remote station in Portugal. The SMC remote stations distribution (b) in Azores (c) across continental Portugal (top) and in Madeira (bottom).

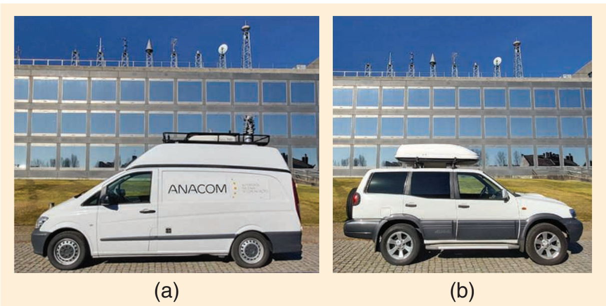


FIGURE 4. ANACOM SMC mobile stations in Porto. (a) General purpose SMC mobile station. (b) All-terrain SMC mobile station with radiogoniometry capabilities.

that a particular RFI affecting a particular frequency band simultaneously impacts the importance and effectiveness of the data measured in other frequency bands. The understanding of these particularities of an EESS or MetSat by administrations is not always clear-cut, but it is important in implementing a suitable spectrum monitoring and enforcement policy addressing EO mission requirements.

Before mobilizing and deploying further resources, fixed SMC infrastructure is used to gather the first evidence, providing the first intelligence for the further study of the case at hand. In this sense, the technical characteristics and operational parameters of the affected station are also studied to check compliance with the in-force regulatory framework and frequency assignment conditions for operation. Because the action range of spectrum authority officers is established by law, nonconforming frequency assignments void all possible grounds for protection actions, and in such circumstances, stations affected by RFI will not be entitled to any radio protection whatsoever, as such RFI is and should be expected.

Then, a targeted action plan is prepared and deployed to ensure the most effective and efficient investigation of the reported anomaly. Where possible, the affected station will be inspected to exclude the scenario of an anomaly due to causes internal to the station itself and to establish a first RFI scenario, if any. Further investigations will be carried forward on the basis of the provided and/or collected evidence technically characterizing the RFI and providing its signature, which is used in localizing and identifying its cause.

Based on the established RFI scenario, the affected area is delimited, and a preliminary localization is estimated. The precise localization is found by starting from the first reference available, i.e., the area where the RFI was first detected, and expanding the investigation area from there. It is thus very important to provide a "first guess" for that location (and respective accuracy/uncertainty) that is as precise as possible to localize the source, understand the cause, and take the required remedial actions in a timely manner. This is particularly important in cases of space services, considering their large footprint.

The unknown RFI source's technical characteristics and operational configuration call for a resilient and nondiscriminatory approach in investigating an RFI scenario that needs to be figured out. There will be constraints on physically accessing areas important for the investigation, due either to the orography or available infrastructure enabling that access. Furthermore, the dynamics of the source of RFI in terms of its RF signal characteristics and location (either static or moving) will play an important role in the course of the investigation, along with many other factors, for example, the propagation mechanisms and phenomena, which must be duly considered in understanding whether the officers are supposed to be detecting the RFI at that time and location or not and in which conditions, duly noting that the affected payloads are very sensitive. In this sense, the payloads are particularly susceptible to RFI, for which case it is particularly important to observe and comply with article 3 as well as article 4 of the RRs (including provisions 3.3, 3.11–3.13, 4.1, 4.5, and 4.7) from the early stages of the mission development process. Finally, it is necessary to stress the role of the frequency response of the propagation characteristics, which will inevitably pose the need for tighter requirements in estimating the first reference as the frequency increases.

As part of the investigation, it is very important to have regular exchanges of information between the spectrum authority officers mobilized for intervention and the affected operator to understand the evolution of the dynamics of the RFI and correlate findings in the field with observations made on the side of the compromised system. This is particularly challenging in the course of investigations involving space stations in nongeostationary orbits, for there is a revisit time to consider and wait for, which further challenges radio protection proportional to latitude.

Once the RFI source is localized, the system originating it will be identified along with the responsible entity for that system. The cause of the RFI is then technically studied, and the required remedial actions are taken to mitigate it. Notwithstanding the RFI mitigation, possible transgressions against applicable laws and regulations are identified to adopt the required precautionary measures and apply the appropriate sanctions provided for by law, which may include seizing equipment and collecting fines. These particulars are widely variable from country to country and are out of the scope of this contribution.

HARMFUL INTERFERENCE IN EARTH OBSERVATION MISSIONS IN PORTUGAL

Portugal's experience with protecting EO missions lies with the European Space Agency Soil Moisture and Ocean Salinity (SMOS) mission, which is the only source of the country's received reports of harmful interference (directly, via the administration and SIRRS) affecting EO missions. Different RFI sources have been found in the SMOS assigned frequency band of 1,400–1,427 MHz [28]. The identified RFI sources include harmonic emissions caused by the excessive power of terrestrial TV broadcasting stations, as well as intermodulation products resulting from emissions from different TV broadcasting stations using different technologies (Figure 5).

Other RFI sources include self-oscillating TV receiving circuits equipped with low-noise amplifiers and whose termination is in open circuit. Some examples are shown in Figures 6 and 7. These sources have the particularity that

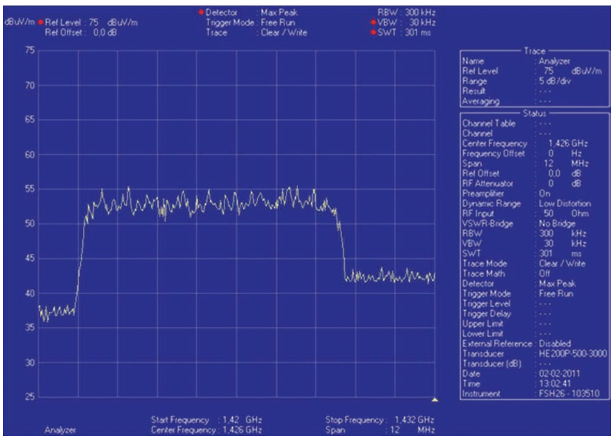


FIGURE 5. The emission of a second-order intermodulation product in the 1421.3–1429.3-MHz band, resulting from two stations in the broadcasting service operating at 583.25 MHz and in the 838–846-MHz range.

they are highly unstable in power, time, and frequency, being able to exhibit unpredictable RF behaviors that also depend on environmental factors. Furthermore, they are usually located on private property, which requires the cooperation of the responsible parties. For that, much depends on the right approach of the spectrum authority officers in handling the situation [29]; in general, “civic skills” constitute an important capability of administrations, which are especially critical in all spectrum-related matters related to the general population (since RF spectrum is not experienced in an obvious manner by human senses, it may be a foreign concept for most people); for an example of what such “public diplomacy” expertise might entail, see [30] and [31].

Finally, significant efforts have been made in providing radio protection to stations in mobile service implementing International Mobile Telecommunications (IMT), as well as in enforcing spectrum sharing and coexistence conditions for wireless access systems (WAS), including radio local area networks (RLAN). The first has been affected by unstable fundamental as well as spurious emissions of systems similar to those in Figures 6 and 7, which fall in the EESS (both passive and active) bands, including the previously mentioned one. By solving these cases affecting IMT stations, their possible effect on EO missions in an EESS is prevented. On the other hand, monitoring and controlling WAS/RLAN deployment (in terms of emissions, spectrum occupancy, and intensity of use) and enforcing compliance with the expected operational configuration (e.g., indoors versus outdoors) has been a practice of preventive radio protection from excessive emissions.

FINAL REMARKS AND FUTURE PERSPECTIVES

EO missions play an essential role in climate action, are an integrant part of the digital transition ecosystem, and enable a wide range of unique services and applications, including those in the framework of “smart tourism” and “e-agriculture,” that cannot be provided by any other means. By operating stations in radiocommunication services, they are subject to the regulatory and supervisory provisions of national administrations, but they also benefit from radio protection against harmful interference, which is essential for their safe, effective, efficient, and economical development and operation, especially in an environment of ever-growing numbers of missions, devices, and applications that rely every day on spectrum use.

Notwithstanding the required means to accommodate the impact RFI has on services provision, claiming radio protection and restoring the expected radio environment constitute the *de facto* RFI mitigation. For that, radio protection needs to be claimed in the form of RFI reporting, which should always be done regardless of the spectrum sharing and compatibility scenario (including with active services), for there is a due technical and legal sharing framework to be monitored and enforced (see Figure 8). Should the claimed interference be of a permissible nature, an appropriate answer should be provided nonetheless. Findings in this respect are also useful in supporting future regulatory measures to adequately protect relevant radiocommunication services because the conceptuality put forward in the spectrum policy and regulatory domains becomes real only after its enforcement in the field [32]. As a matter of fact, an effective control of spectrum use plays, and may further play, a key active role in supporting the development and deployment of novel spectrum sharing models and scenarios [33], including those that otherwise would not be possible without risking jeopardizing the existing coexistence between services and technologies.

To be successful in pursuing their mission, administrations must take action to duly empower themselves with enforceable instruments (legal, regulatory, technical, and so on). Moreover, in facing a claim for radio protection, administrations should take prompt actions to duly investigate

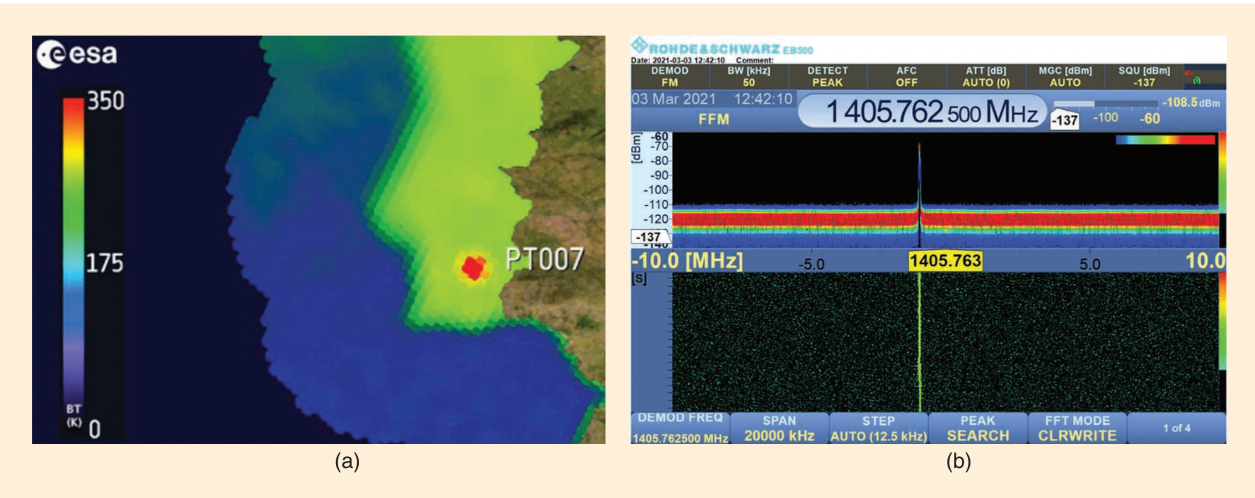


FIGURE 6. The emission of a TV receiving system: the (a) impact on EO products and (b) spectral signature.

the case, adopt the appropriate remedial actions, and provide an effective answer in a timely manner. The high sensitivity of EO sensors, their large footprint, and the geometry of the RFI scenario make these cases particularly challenging to solve regardless the RFI source, requiring extreme technical and operational agility and flexibility to overcome complex scenarios and challenging (natural and human) environments far from the prompt support of the office. Nevertheless, the Portuguese administration's experience in solving harmful interference to EO missions may serve as evidence that harmful interference-free spectrum use is effectively possible (see Figure 9). It is also argued that the nurturing of both (soft) "civic skills" and (hard) knowledge building capabilities may well be a pathway to sustaining the effective role of administrations as the sociotechnical landscape becomes ever more complex [34], [35], [36], [37].

With the ever-increasing use of RF spectrum and associated orbit resources by EO missions as well as by so many other systems and technologies, one can expect increasing challenges related to spectrum sharing. Ensuring the sustainability of outer space, that is to say, the provision of continued effective access to space, requires the rational and efficient use of scarce orbital and spectral resources. For this aim, forward-looking EO mission setups are required to be increasingly productive, which can happen only by maximizing their performance by securing their operation in a harmful interference-free environment. In this sense, future EO missions need to empower themselves with the required tools for claiming radio protection to ensure that the geoscience and remote sensing and meteorological communities will be able to both address the emergent challenges and leverage from the opportunities set to present themselves in the coming decades.

In a nutshell, it is essential to ensure today the full compliance with applicable regulations and recommendations, take precautionary measures proportional to the particular susceptibility of a mission to RFI, and tighten RFI detection and geolocation requirements as the frequency increases to claim protection tomorrow by reporting RFI (noting that what is not reported is assumed not to exist), and administrations must deploy a full range of capabilities that frame and empower the smooth activity of EO missions, allowing them to fulfill their role in engaging grand societal challenges.

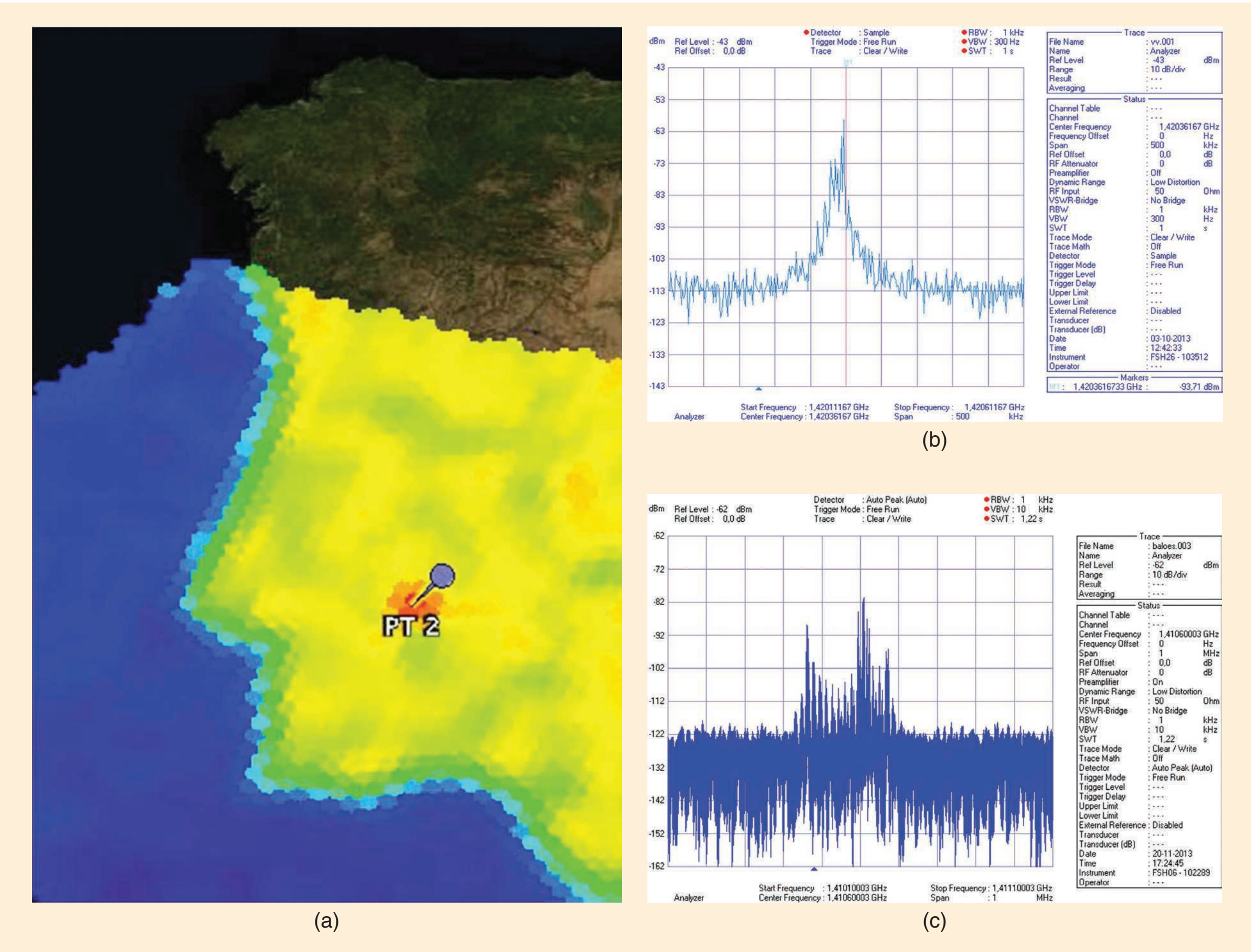


FIGURE 7. Aggregation of two interfering TV receiving systems. The (a) impact on EO products, (b) spectral signature of one interference source, and (c) spectral signature of a second different interference source in the same neighborhood.

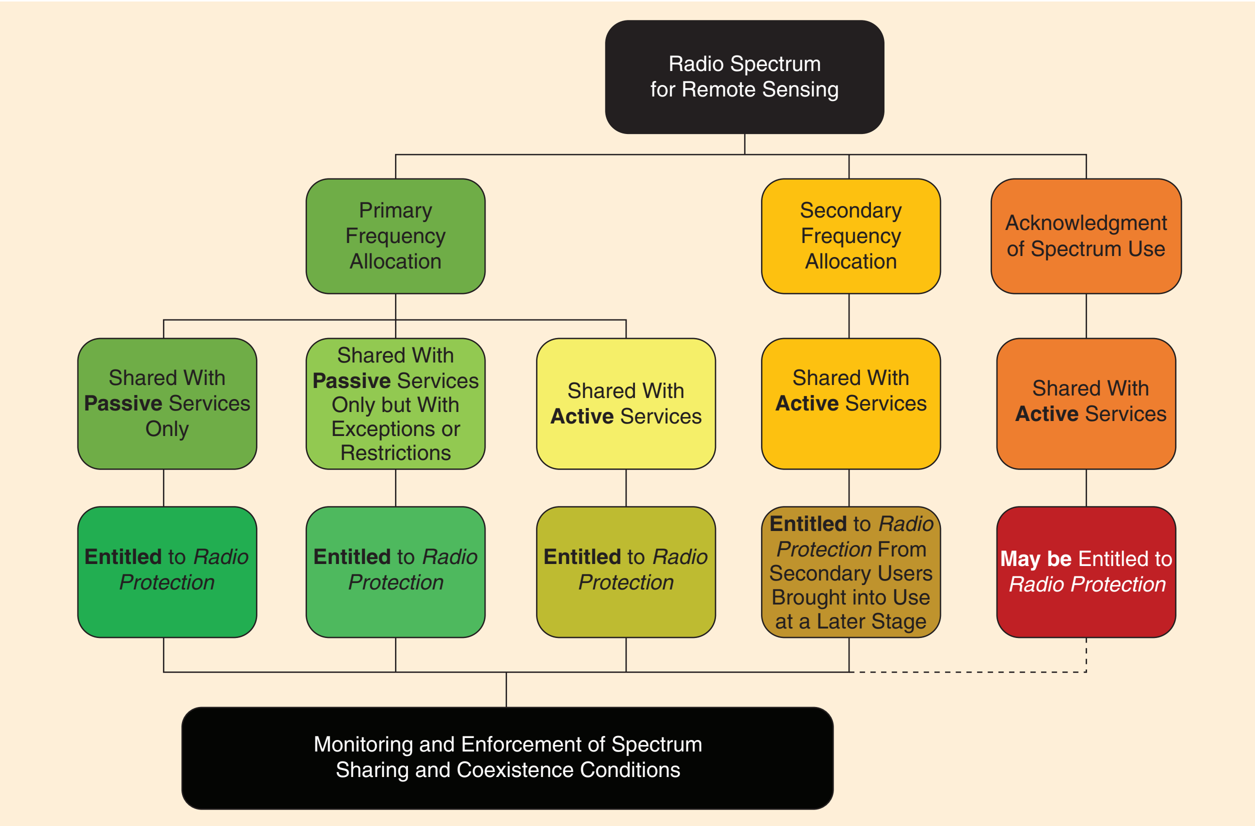


FIGURE 8. The categories of radio spectrum use for remote sensing and respective entitlement to radio protection.

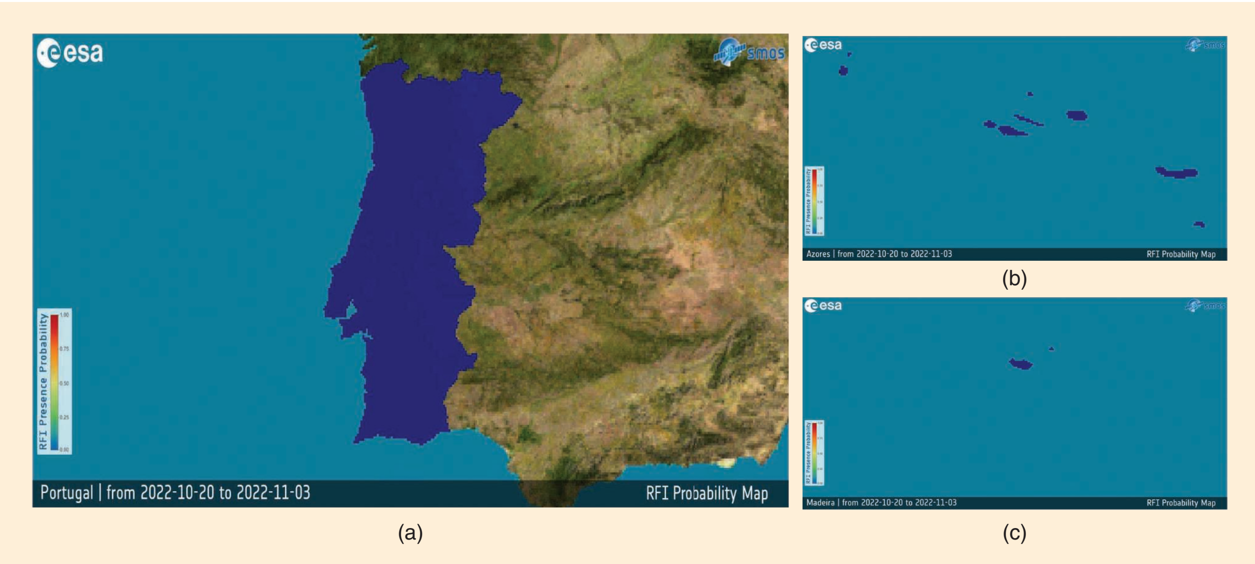


FIGURE 9. RFI presence probability maps of the European Space Agency Soil Moisture and Ocean Salinity mission, evidencing an RFI-free operational environment, over Portugal. (a) Continental Portugal, (b) Azores, and (c) Madeira.

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