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Channel Model for Terrestrial Fixed Service Interference to Aeronautical Satellite Receivers

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- For Mom and Dad -

Abstract

Radio frequency interference is increasingly affecting radio communication systems in the geostationary satellite orbit. This interference is caused by a growing number of closely spaced satellite networks, overlapping coverage areas, and the intensive use of the limited radio spectrum. Particularly affected is the fixed-satellite service in the K- and Ka-bands. Since the 2019 World Radiocommunication Conference, this spectrum has been authorized to provide broadband services to aircraft (“in-flight entertainment”) via satellite. The K- and Ka- band spectrum is heavily utilized by terrestrial radiocommunication service, such as fixed point-to-point microwave links. The use of these frequency bands by aeronautical earth stations in the fixed-satellite service, in accordance with regulations, is only possible with the acceptance of interference from terrestrial radiocommunication services.

This thesis investigates the interference potential of terrestrial fixed service links on aeronautical earth stations in the fixed-satellite service communicating with geostationary satellite orbit networks. Physical, technical, operational, and regulatory constraints are considered, from which an analytical interference channel model is formulated. The statistical characteristics of the radio frequency interference in the aeronautical satellite receiver are determined based on extensive geometric simulations, and the resulting impacts on the broadband satellite link are quantified. Building on this, a novel, scalable stochastic channel model is developed. Thereby, representative interference channel states for a higher-order Markov process are derived by Vector quantization. The Markov chain enables a realistic representation of the statistical distribution functions and the temporal dynamics of the interference. The capability to scale the model to different frequencies, antenna diameters, and flight velocities is developed. In addition, a concept for an experimental measurement campaign is presented to validate the model assumptions.

The results provide a scalable, regulation-compliant channel model for terrestrial fixed service interference to aeronautical satellite receivers in the 17.7-19.7 GHz frequency range. This channel model supports the design of resilient aeronautical satellite communication systems in shared frequency band. Furthermore, it offers a foundation for developing mitigation measures for interference reduction.

Kurzfassung

Funkstörungen beeinträchtigen zunehmend Kommunikationssysteme im geostationären Satellitenorbit. Diese entstehen durch eine steigende Zahl eng benachbarter Satellitennetzwerke, überlappende Ausleuchtzonen und der intensiven Nutzung des limitierten Funkpektrums. Besonders betroffen ist der feste Funkdienst über Satelliten im K- und Ka-Band. Seit der Weltfunkkonferenz 2019 ist dieses Spektrum für die Bereitstellung von Breitbanddiensten im Flugzeug („In-Flight Entertainment“) über Satelliten zugelassen. Das K- und Ka-Band Spektrum wird ebenfalls intensiv durch terrestrische Funkdienste, wie dem Richtfunk genutzt. Die zusätzliche Nutzung dieses Frequenzbereiches durch aeronautische Bodenstationen im festen Funkdienst über Satelliten ist gemäß den geltenden Regularien nur möglich, wenn Störungen durch terrestrische Funkdienste akzeptiert werden.

Diese Arbeit untersucht das Störpotenzial des terrestrischen Richtfunks auf aeronautische Erdefunkstellen im festen Satellitenfunk. Es werden physikalische, technische, operative und regulatorische Randbedingungen berücksichtigt und daraus ein analytisches Kanalmodell der Funkstörungen formuliert. Auf Basis umfangreicher geometrischer Simulationen werden die statistischen Eigenschaften der Funkstörungen im aeronautischen Satellitenempfänger bestimmt und die Einflüsse auf die breitbandige Satellitenverbindung quantifiziert. Darauf aufbauend wird ein neuartiges, skalierbares stochastisches Kanalmodell entwickelt. Hierzu werden repräsentative Kanalzustände für eine Markov-Kette höherer Ordnung durch Vektorquantisierung ermittelt. Mit der Markov-Kette können statistischen Verteilungsfunktionen und die zeitliche Dynamik der Störung realistisch abgebildet werden. Zudem wird die Skalierbarkeit dieses Modells auf verschiedene Frequenzen, Antennendurchmesser und Fluggeschwindigkeiten, erarbeitet. Ergänzend wird ein Konzept für eine luftgestützte Messkampagne vorgestellt, um die Modellannahmen experimentell zu validieren.

Die Ergebnisse liefern ein skalierbares, regulierungskonformes Kanalmodell für Störungen des terrestrischen Richtfunks in aeronautischen Satellitenempfängern im Frequenzbereich 17,7-19,7 GHz. Dieses Kanalmodell unterstützt die Auslegung von robusteren aeronautischen Satellitenkommunikationssystemen in Frequenzbändern, welche mit anderen Funkdiensten geteilt werden müssen. Dies bietet eine Grundlage für die Entwicklung von Gegenmaßnahmen zur Interferenzreduktion.

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1 Introduction

1.1 Motivation

The increasing demand for ubiquitous broadband connectivity, enabling access to the World Wide Web anywhere and anytime, is challenging for all telecommunications providers. Checking emails, staying in contact with friends, streaming videos, or transferring a large amount of data is a matter of course in times of global connectivity. In areas where terrestrial infrastructure is underdeveloped, connection to terrestrial communication systems is impossible, or where large areas shall be served, satellite communication (SATCOM) is optimal for providing seamless and global connectivity for any receive terminal. Arthur C. Clarke already demonstrated in 1945 that three satellites in the geostationary satellite orbit (GSO) are sufficient to give worldwide radio coverage [1].

Nowadays, GSO networks are the most deployed and developed SATCOM resource in space. Satellites in the GSO are used for weather and climate forecasting, television and radio broadcasting, remote sensing, secure governmental and military applications, and, most often, broadband connectivity. GSO networks, a crucial pillar in the context and development of the 5th and 6th generation of wireless networks [2, 3], have become competitive with non-GSO satellite constellations in the low Earth orbit (LEO) and medium Earth orbit (MEO). Especially LEO systems provide higher capacity with lower latency and smaller ground terminals. However, despite rapidly emerging non-GSO broadband constellations like Starlink from SpaceX [4] and Project Kuiper [5] of Amazon, GSO networks remain essential for providing global broadband connectivity.

One of the most significant challenges of GSO networks is the limited space along the GSO arc that is available for new networks. Attractive hotspots for service provision over the Americas, Africa, the Middle East, Europe, and Asia result in narrow spacing and competition for spectrum access among satellite networks in the GSO arc. When GSO satellites provide similar services over the same areas of interest, they cause adjacent-satellite interference (ASI) [6, 7]. New entrants in the GSO market must spend considerable effort and time for their spectrum access in an interference-limited environment and might adhere to strict operational power limits. The use of and access to spectrum is regulated by international coordination rules to protect existing networks and systems. These rules are set out in the International Telecommunication Union-Radiocommunication Sector (International Telecommunication Union-Radiocommunication Sector (ITU-R)) Radio Regulations (ITU-RR) [8] in its four Volumes (Vols.) and the corresponding Rules of Procedure (RoP) [9], as depicted in Fig. 1, allowing for international recognition but under the protection of existing network. The four Vols. cover different topics in spectrum

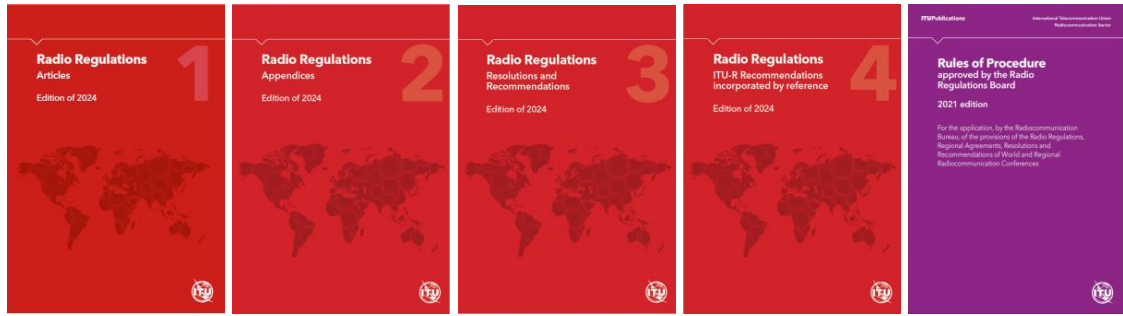


Figure 1: Most relevant regulatory documents in satellite communications: the four volumes of the International Telecommunication Union Radio Regulations (Edition 2024) [8] and the Rules of Procedure (Edition 2021) [9].

regulation. Vol. I, the most important, covers the articles, Vol. II includes technical Appendices, Vol. III lists Resolutions (Res.s) referenced in the footnotes, and Vol. IV lists the Recommendation (Recs.) incorporated by reference in the ITU-RR. The RoP complement those in cases where ambiguities arise, or a process is required to implement regulatory provisions from the ITU-RR.

When access to the satellite spectrum is power-limited and interference-congested, interference mitigation methods and robust transmission techniques become significant for GSO operators. The design and deployment of high throughput satellites (HTSs) in the GSO, allowing frequency reuse by multibeam architectures, were a logical evolution. They cover the continuous demand for increased throughput in a limited spectrum allocated to space radiocommunication services, such as the fixed-satellite service (FSS). HTSs, like SES-17, having 200 Ka-band beams [10], or Viasat 3 employing more than 1 000 beams, providing a total throughput of more than 1 Tbit/s [11], efficiently reuse spectrum within its field of view (FOV) by allocating different frequency ranges and polarization to each beam.

With these multibeam architectures, a new field of transmission schemes can be applied to optimize the throughput in a competitive interference environment. The multiple transmit and receive antennas at the satellite can be used for spatial diversity, reducing ASI in satellite downlinks [12], improving interference susceptibility [13], and increasing eavesdropping resistance [14].

One primary application of GSO HTSs is aeronautical communication for broadband in-flight entertainment (IFE). GSO HTSs are predestined to connect long-haul flights. Even for considerable distances covering multiple continents, seamless connectivity can be guaranteed throughout the flight using only one or a maximum of two satellites due to the large FOV as seen from the GSO. Fig. 2 shows the coverage of exemplary GSO networks covering the major commercial airline routes [15], which the Société Européenne

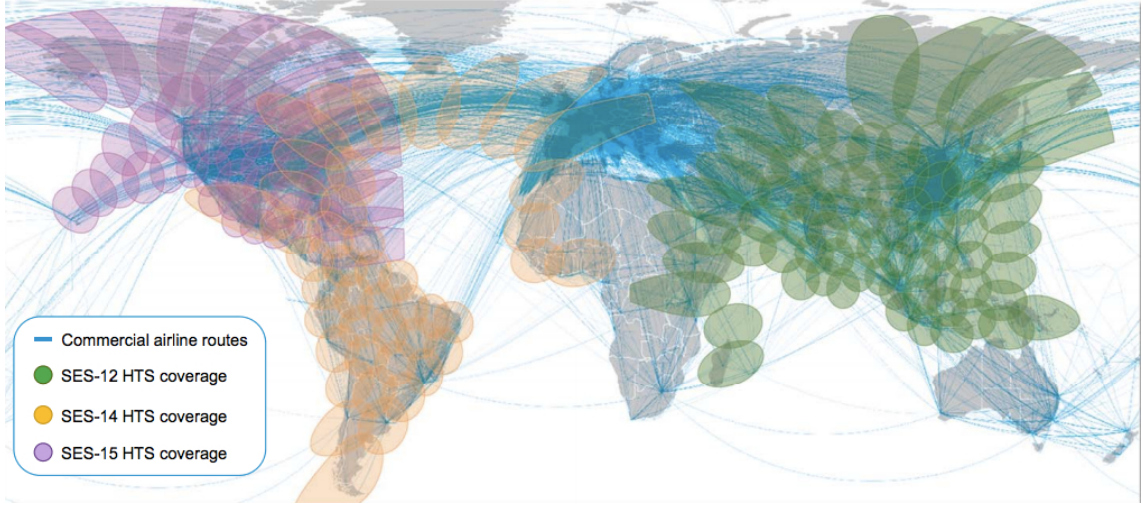


Figure 2: Coverage of a representative constellation of three Société Européenne des Satellites geostationary satellite orbit networks that provide global connectivity along major commercial airline routes [15].

des Satellites (SES) arbitrarily owns.

On the other side, providing this service to aeronautical earth stations onboard an aircraft (AC) is challenging for satellite operators. The limited space on the aircraft and the need to minimize aerodynamic drag to reduce fuel consumption constrain the type and size of aeronautical SATCOM antennas used for IFE. Small antenna diameters at the aircraft do not sufficiently amplify the received signals. To allow for high throughput the low antenna gain at the aircraft must be compensated by a high antenna gain at the satellite, increasing costs and risks when building and deploying a GSO satellite [16, 17].

Moreover, providing broadband connectivity on large aircraft such as an Airbus A380-800 presents additional challenges. Depending on the airline's cabin configuration, up to 500 passengers [18] may simultaneously desire access to the internet. These power and antenna size constraints limit the use of spectrally efficient transmission techniques, necessitating robust modulation and coding schemes that occupy more spectrum. Offering reliable throughput and quality of service for IFE to users onboard an aircraft, despite antenna diameter and transmit power limitations, requires sufficient broadband spectrum.

Satellite capacity and ground station technology to satisfy the large bandwidth requirements on a globally harmonized basis can be found, *inter alia*, in the K- and Ka-bands [19], respectively, in the frequency ranges 27.5-30 GHz in the Earth-to-space direction (uplink) and 17.7-20.2 GHz in the space-to-Earth direction (downlink). These frequency ranges are allocated to the FSS in the ITU-RR.

SATCOM receivers onboard aircraft mismatch the definition of FSS, which belong to the mobile-satellite service (MSS). MSS is allocated to the K- and Ka-bands only in a fraction of the above-listed frequency ranges and is not globally harmonized. The definition of the FSS, limited to communication between fixed points, allows the operation of

multiple radiocommunication services sharing the same frequency bands.

Geographic separation of transmitting and receiving stations of different services provides spatial discrimination for co-frequency operation, which is impossible for the so-called earth stations in motion (ESIMs). ESIMs are quasi-mobile earth stations (land mobile, aeronautical, or maritime earth stations) operating in frequency allocations of the FSS. Moving stations continuously change locations, not allowing a co-frequency operation based on distinct geographic separations from a regulatory perspective.

The World Radiocommunication Conference (WRC) in 2019, *inter alia*, resolved that FSS spectrum in the frequency range 17.7-19.7 GHz and 27.5-29.5 GHz can be used by ESIMs under certain conditions and limitations, even when shared with other radiocommunications services. Most important is sharing with terrestrial services, such as fixed point-to-point and point-to-multipoint links, which are intensively using the K- and Ka-band frequency ranges.

To protect terrestrial radiocommunication services from harmful radio frequency interference (RFI), ESIMs using the FSS K- and Ka-band spectrum are limited in transmit power. Moreover, ESIMs are obliged to accept the RFI caused by emissions from stations of terrestrial radiocommunication services. Hence, operators of terrestrial stations have no responsibility to protect (e.g., by comparable power limits) receiving ESIMs operating in the FSS. These conditions further aggravate the provision of IFE services. In a scenario with a high demand for throughput, satellite operators must now comply with regulatory power limits to protect terrestrial services, operational limits to protect adjacent satellite networks, and, more severely, accept unknown time variant RFI from stations of incumbent terrestrial radiocommunication services.

Compared to land mobile and maritime ESIMs, aeronautical-earth stations in motion (A-ESIMs) are more susceptible to terrestrial RFI. The number of co-frequency terrestrial stations within the radio horizon of the aircraft receiver increases with flight altitude. Unlike terrestrial paths, where buildings, landscapes, or vegetation obstruct unwanted main- and sidelobe emissions from stations of terrestrial radio services, aeronautical receivers cannot benefit from those attenuations. At cruising altitude, aircraft are not subject to significant clutter, diffraction, obstruction, or shadowing effects as terrestrial systems.

Consequently, when flying through the main lobe of an interfering transmitter, the interference is received with minimal attenuation beyond free-space path loss. In contrast, aeronautical receivers in an air-to-ground path can receive interference power without significant attenuation. The only discrimination, respectively, attenuation would occur by the off-axis discrimination of both the receiving and transmitting antenna and the atmospheric propagation losses.

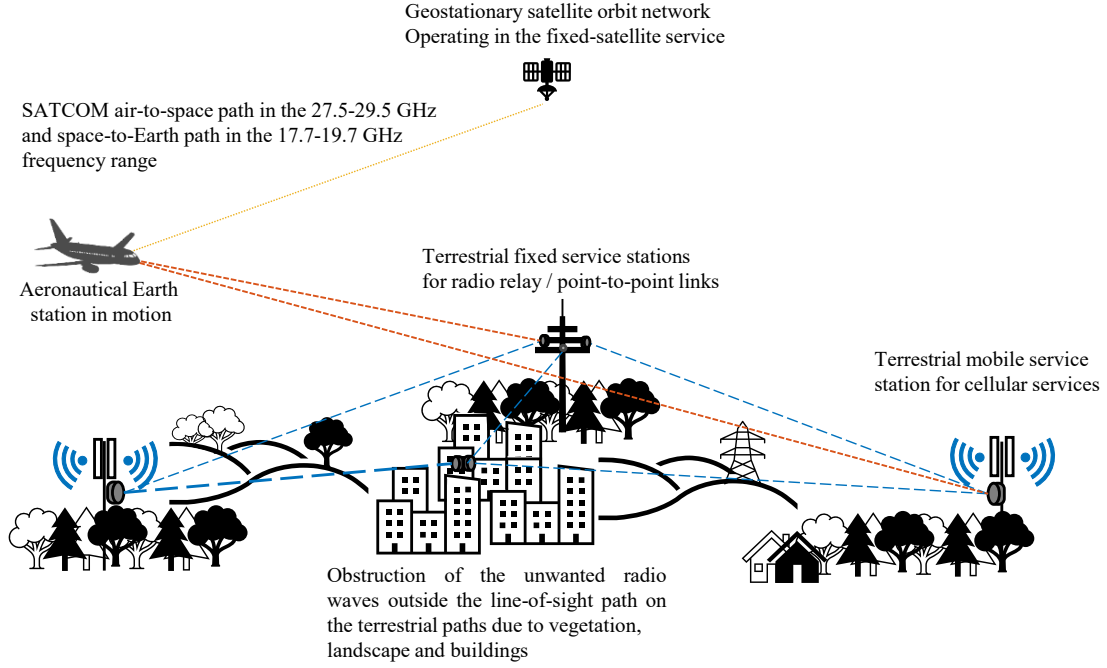


Figure 3: Interference scenario for an aeronautical earth station in motion receiving radio-frequency interference from co-frequency emissions of terrestrial radio stations.

Fig. 3 depicts the described interference scenario for an A-ESIM that receives RFI due to co-frequency emissions of terrestrial radio stations not obstructed by vegetation, buildings, or landscape.

Usually, regulatory power limits enforced by ITU-R can be quantified and considered in the system and link design as they are known parameters. Similarly, operational limitations stemming from coordination with other satellite operators are well known. Each GSO operator can influence those operational limits in bilateral frequency coordination meetings. The RFI from stations of terrestrial radiocommunication services, in particular, the mobile service (MS) and the fixed service (FS), depends on the geographical location of the A-ESIM, the actual deployment characteristics of the terrestrial stations, and their temporary use. As there is no reporting requirement for the use of terrestrial services, an A-ESIM operator cannot determine the impact on its networks in detail *a priori*.

Moreover, to date, there are no regulations in force for deploying stations of terrestrial services concerning the protection of the GSO, the FSS, and associated Earth stations. The regulatory Provision (No.) for terrestrial services sharing bands above 1 GHz (ITU-RR No. 21.3) limits the equivalent isotropically radiated power (EIRP) for transmitting stations to $\text{EIRP} \leq +55 \text{ dBW}$ in the direction of the GSO.

Additionally, each country is not obligated to record and report the deployment of terrestrial stations and their characteristics. The acceptance of RFI caused by FS and MS transmitters in the 17.7-19.7 GHz frequency range is left for the ESIM operators to cope with. Given the increasing reliance on SATCOM for aeronautical applications,

particularly in commercial aviation, RFI from stations of terrestrial radiocommunication services is toxic for maintaining service quality. As more terrestrial systems are deployed and spectrum usage intensifies, understanding the nature of this interference becomes increasingly essential. FS stations using high-power, highly directive antennas for long-distance terrestrial links have the highest potential for causing interference with ESIM links, particularly those used in aeronautical SATCOM systems.

Stations of the MS with sectorial base stations covering smaller areas and using omnidirectional antennas, combined with limited transmit power capabilities, contribute less to interference over long distances towards flight altitudes. Furthermore, the use of MS in the K- and Ka-band frequency ranges is still underdeveloped.

This thesis aims to develop a comprehensive model that integrates empirical and deterministic simulations of RFI caused by FS systems in the 17.7-19.7 GHz band into A-ESIM SATCOM receivers. The impact of aggregate FS RFI into the aeronautical SATCOM channel used by A-ESIMs in the 17.7-19.7 GHz frequency range is assessed and quantified to provide an analytical and stochastic channel model for a fast and reliable estimation and prediction of interference. This channel model supports creating more resilient SATCOM systems, ensuring reliable communication links even in varying interference conditions. With that, the efficient use of the limited resource spectrum is enhanced by providing more accurate interference predictions, essential for minimizing RFI in the heavily used and congested FSS frequency bands.

Key Takeaway

The 17.7-19.7 GHz downlink band is globally allocated on a primary basis to the FSS and, since WRC-19, can also be used by ESIMs, despite being shared with terrestrial fixed and mobile services. Historically, FSS was restricted to communication between fixed points. ESIMs, and in particular A-ESIMs, required special regulatory provisions. The WRC-19-changes enabled their operation in this band, subject to regulatory conditions, that require acceptance of terrestrial interference, a factor relevant to global IFE services.

1.2 Regulatory Background

This section provides a high-level summary of the applicable regulations for operating FSS networks in the K- and Ka-bands. It also outlines the specific regulatory framework of A-ESIMs enforced by WRC-19 in Res. **169** and revised by WRC-23 (**Rev. WRC-23**). All Provisions and Resolution incorporated by law are highlighted in bold letters, following the nomenclature and references of the ITU-R.

The ITU-RRs, which define the international framework for the spectrum use of all radiocommunication services, are the foundation of all regulatory provisions. Vol. I and its articles (Arts.) **1**, **5**, **9**, **11**, and **21** are the key components of these regulations. Art. **1** covers the definition of radiocommunication services, Art. **5** the regulations for accessing spectrum, Arts. **9** and **11** provide requirements for the coordination and notification between co-frequency applications, services, and stations. Finally, Art. **21** includes limits for terrestrial and space services sharing frequency bands above 1 GHz.

Regional groups and committees like the Conférence Européenne des Administrations des Postes et des Télécommunications Electronic Communications Committee (CEPT ECC), the Inter-American Telecommunication Commission (CITEL), and national regulators like the German Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (BNetzA), or the United States Federal Communications Commission (FCC), play a crucial role in building on these regulations and have the right to add more constraints for national implementation. Their collaborative efforts in the International Telecommunication Union (ITU)-process ensure a comprehensive and effective regulatory framework.

1.2.1 Allocations in the 17.7-19.7 GHz Frequency Range

Art. **5** in Vol. I of the ITU-RR regulates the spectrum use of radiocommunication services in the Frequency Allocation Table. In that table, radiocommunication services are allocated to particular frequency ranges that may differ among the three ITU-Regions. These Regions are depicted in Fig. 4. The boundaries of each ITU-Region are defined in the ITU-RR Art. **5** Nos. **5.3**, **5.4**, and **5.4**. ITU-Region 1 covers Europe, Africa, and all countries above China, Pakistan, Afghanistan, and Iran. ITU-Region 2 comprises the Americas, and ITU-Region 3 includes the remaining Asian Pacific countries. Compared to the typical service area(s) of a GSO IFE service provider (see Fig. 2), all three ITU-Regions are subject to spectrum use by A-ESIMs in the K- and Ka-bands. The K- and Ka-band frequency ranges allocated to the FSS in the space-to-Earth direction and the other incumbent radio services are extracted from the ITU-RR Art. **5** and are shown in Table 1. The relevant descriptions to understand the frequency allocation table from

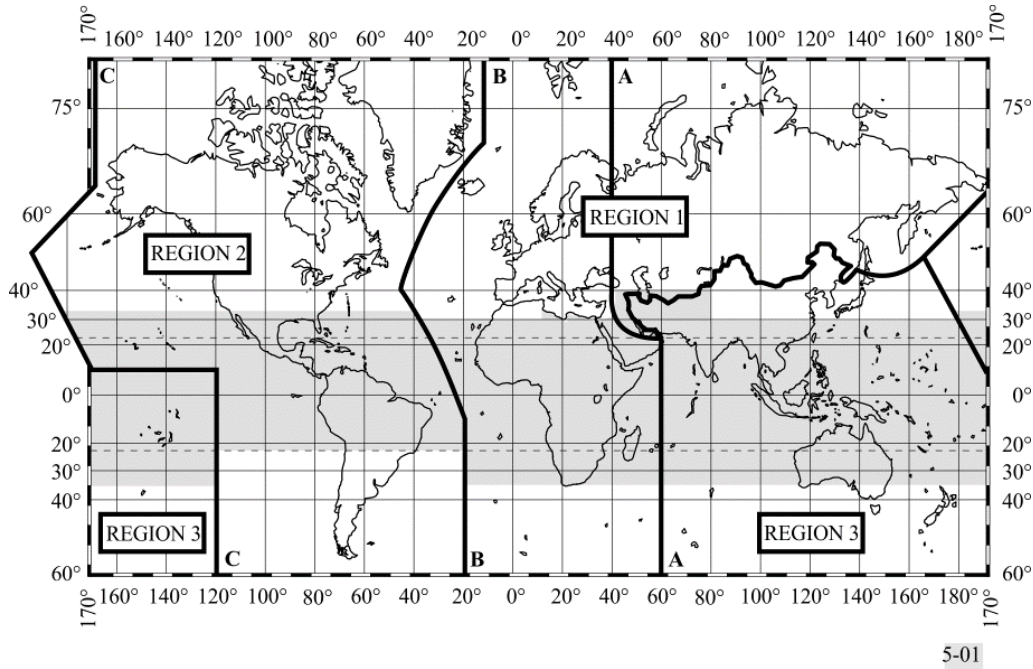


Figure 4: Division of the Earth into three regions according to Article 5 of the International Telecommunication Union Radio Regulations [8], covering the Americas (Region 2), Europe, Africa, and Russia (Region 1), and the Asia-Pacific (Region 3).

ITU-RR Nos. **5.23** to **5.52** are repeated hereafter:

- Services whose names are printed in capitals (e.g., “FIXED”) are called primary services, whereas services whose names are printed in regular characters (e.g., “Mobile”) are called secondary services.
- The heading of the Frequency Allocation Table includes three columns, each corresponding to one of the three ITU-Regions.
- A worldwide or a regional allocation occupies the whole table width or only one or two of the three columns.
- Within each cell, the services are listed alphabetically according to the French language. The order of listing does not indicate relative priority within each category.
- When there is a parenthetical addition to an allocation in the Table, that service allocation is restricted to the type of operation indicated (e.g., “space-to-Earth”).
- The footnote references that appear to the right of the name of a service apply only to that particular service.

The gray highlighted parts in Table 1, added for this thesis, show that the FSS (space-to-Earth) has a worldwide (i.e. globally harmonized) primary allocation for the entire 2.5 GHz and that the footnote ITU-RR No. **5.517A**, referring to Res. **169 (Rev. WRC-23)** and the use of ESIMs, is added only to the lower 2 GHz from 17.7-19.7 GHz:

"5.517A The operation of earth stations in motion communicating with geostationary fixed-satellite service space stations within the frequency bands 17.7-19.7 GHz (space-to-Earth) and 27.5-29.5 GHz (Earth-to-space) shall be subject to the application of Resolution **169 (Rev. WRC-23)**. (WRC-23)." (ITU-RR, 2024, p. 164)

It shall be noted that the frequency range 19.7-20.2 GHz and the corresponding uplink in the 29.5-30 GHz frequency range is subject to Res. **156 (Revision (Rev.) WRC-23)** by footnote ITU-RR No. **5.527A**, allowing the use of ESIMs, too, but having different perspectives. Despite having a secondary and a primary MSS allocation, terrestrial radio-communications services in the concerned frequency band are allocated on a secondary basis via a country footnote in ITU-RR Nos. **5.524** and **5.542**. However, Res. **156 (Rev. WRC-23)** and the use of ESIMs in the 19.7-20.2 GHz frequency range is outside of the scope of this thesis, although the principles developed in this theses can be applied to that portion of the K- and Ka-band frequency ranges, too.

Before WRC-19, the use of worldwide 2.5 GHz spectrum allocated to primary FSS for aeronautical communication, respectively, for A-ESIMs, was not allowed. It required extra regulations referenced by a footnote in the frequency allocation table. The reason for this is the definition of the FSS in ITU-RR No. **1.21**:

"1.21 *fixed-satellite service: A radiocommunication service between earth stations at given positions when one or more satellites are used; the given position may be a specified fixed point or any fixed point within specified areas; in some cases, this service includes satellite-to-satellite links, which may also be operated in the inter-satellite service; the fixed-satellite service may also include feeder links for other space radiocommunication services.*" (ITU-RR, 2024, p. 8)

This definition restricts the communication between FSS networks to fixed points, facilitating the sharing of spectrum with co-frequent stations of other radiocommunication services. The frequency range 17.7-19.7 GHz (space-to-Earth) is allocated to terrestrial FS and MS on a primary basis, too, requiring coordination among stations to enable co-frequency operation. An A-ESIM, being an earth station employing a moving nature, would fit more with the definition of the MSS. As per the Table of Frequency Allocations, the MSS has a limited, primary, worldwide allocation of 100 MHz in the 20.1-20.2 GHz frequency range and its corresponding uplink (29.9-30 GHz in the Earth-to-space direction) and 19.7-20.1 GHz in ITU-Region 2, as reflected in Table 1. Additionally, the MSS is allocated on a secondary basis to the 19.7-20.1 GHz in ITU-Regions 1 and 3.

The use of the 19.7-20.2 GHz spectrum for ESIMs is regulated under Res. **156 (Rev. WRC-23)**. The WRC in 2019, among other resolutions, stipulated that primary FSS spectrum in the frequency range 17.7-19.7 GHz and 27.5-29.5 GHz can be used by ESIMs

Table 1: Extract of the Frequency Allocation Table for radiocommunication services in the frequency range 17.7-20.2 GHz [8].

Allocation to services		
Region 1	Region 2	Region 3
17.7-18.1 FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.517A 5.517B (Earth-to-space) 5.516 MOBILE	17.7-17.8 FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.517A 5.517B (Earth-to-space) 5.516 BROADCASTING-SATELLITE Mobile 5.515 17.8-18.1 FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.517A 5.517B (Earth-to-space) 5.516 MOBILE 5.519	17.7-18.1 FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.517A 5.517B (Earth-to-space) 5.516 MOBILE
18.1-18.4	FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.516B 5.517A 5.517B (Earth-to-space) 5.520 MOBILE 5.519 5.521	
18.4-18.6	FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.516B 5.517A 5.517B INTER-SATELLITE 5.521A MOBILE	
18.6-18.8 EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.517A 5.522B MOBILE except aeronautical mobile Space research (passive) 5.522A 5.522C	18.6-18.8 EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.516B 5.517A 5.522B MOBILE except aeronautical mobile SPACE RESEARCH (passive) 5.522A	18.6-18.8 EARTH EXPLORATION-SATELLITE (passive) FIXED FIXED-SATELLITE (space-to-Earth) 5.517A 5.522B MOBILE except aeronautical mobile Space research (passive) 5.522A
18.8-19.3	FIXED FIXED-SATELLITE (space-to-Earth) 5.516B 5.517A 5.517B 5.523B MOBILE	
19.3-19.7	FIXED FIXED-SATELLITE (space-to-Earth) (Earth-to-space) 5.517A 5.523B 5.523C 5.523D 5.523E INTER-SATELLITE 5.521A 5.523DA MOBILE	
19.7-20.1 FIXED-SATELLITE (space-to-Earth) 5.484A 5.484B 5.516B 5.517B 5.527A INTER-SATELLITE 5.521A Mobile-satellite (space-to-Earth) 5.524	19.7-20.1 FIXED-SATELLITE (space-to-Earth) 5.484A 5.484B 5.516B 5.517B 5.527A INTER-SATELLITE 5.521A MOBILE-SATELLITE (space-to-Earth) 5.524 5.525 5.526 5.527 5.528 5.529	19.7-20.1 FIXED-SATELLITE (space-to-Earth) 5.484A 5.484B 5.516B 5.517B 5.527A INTER-SATELLITE 5.521A Mobile-satellite (space-to-Earth) 5.524
20.1-20.2	FIXED FIXED-SATELLITE (space-to-Earth) 5.484A 5.484B 5.516B 5.517B 5.527A MOBILE-SATELLITE (space-to-Earth) INTER-SATELLITE 5.521A 5.524 5.525 5.526 5.527 5.528	

subject to specific conditions and limitations even when the spectrum is shared with primary allocated terrestrial services. The precise details of these conditions and limitations enforced by Res. **169 (Rev. WRC-23)** are outlined in section 1.2.4.

1.2.2 Procedure for Effecting Coordination

Before an administration brings into use a frequency assignment, it shall, according to ITU-RR Art. **9** Section II, effect coordination, as required, with the stations sharing the same frequency bands. Stations in a satellite network using the GSO shall effect coordination in respect of any other satellite network using that orbit under the provision of ITU-RR No. **9.7**. For a transmitting space station of a satellite network, coordination shall be effected in respect of receiving stations of terrestrial services where the coordination threshold value is exceeded under the provision of ITU-RR No. **9.14**. The coordination of an earth station with terrestrial stations or other earth stations operating in the opposite direction of transmission remains according to ITU-RR No. **9.6.2** within the authority of the administration on the territory of which this station is located.

The coordination of GSO networks under ITU-RR No. **9.7** is performed in bilateral coordination meetings in which each operator could negotiate their required protection based on a first-come-first-served principle. I.e., those GSO networks having an earlier date of receipt, respectively, date of protection, can define the conditions under which their network(s) must be protected while recognizing the request for coordination of the other party. An entry in the Master International Frequency Register (MIFR), achieving full recognition and protection of the used frequency assignments, requires the agreement of all identified adjacent GSO networks. The coordination of the GSO significantly impacts the allowed transmit power, and, thus the signal-to-noise ratio (SNR) and spectral efficiency η_{se} .

Secondly, the received interference would further impact the signal-to-interference-plus-noise ratio (SINR), depending on the orbit separation, the requested throughput, and the receiver antenna diameter, which is the antenna on the aircraft, in the case of an A-ESIM. Table 2 provides exemplary GSO link budgets (LBs) for two typical GSO networks separated by 2 degrees on the GSO arc, providing typical IFE services [20] and having a performance objective for a spectral efficiency under ASI conditions of $\eta_{se} \approx 3 \text{ bit}/(\text{s} \cdot \text{Hz})$.

It demonstrates that depending on the priority of the network, severe constraints in transmit power arise, and ASI occurs, which must be compensated by a larger antenna diameter to achieve the same target spectral efficiency. In the example depicted in Table 2, the IFE satellite having no priority, would require a 0.9 m antenna to compensate for the protection requirement of the adjacent interfering satellite for their 0.45 m dishes to achieve the spectral efficiency objectives.

Table 2: Link budget calculation for two geostationary satellite orbit networks providing in-flight entertainment to different aircraft terminal sizes, and the corresponding achievable spectral efficiency according to Recommendation ITU-R S.2131 under adjacent satellite interference.

Parameter	Abbreviation	Unit	IFE satellite	Interfering satellite
Priority			No	Yes
Equivalent isotropically radiated power spectral-density limit	EIRP-SD	dB(W/Hz)	-20	-15
Speed of light in vacuum	c_0	m/s		299 792 458
Frequency	f	GHz	18	18
Elevation	ε	deg.	15	15
Radius of the Earth	r_E	km		6 378.145
Radius of the geostationary satellite orbit	r_{GSO}	km		42 164.2
Distance	d	km	40 060.78	40 060.78
Free space path loss	a_L	dB	209.6	209.6
Antenna diameter	D_{AC}	m	0.9	0.45
Antenna gain	g_{AC}	dB	42.7	36.7
Receive noise temperature	T_N	K	190	190
Orbit separation	φ	deg.		2
Antenna pattern			Rec. ITU-R S.580-6 [21]	
Off-axis gain	$g_{AC}(\phi)$	dB	24.5	21.5
Signal-to-adjacent satellite interference ratio	SIR_{ASI}	dB	16.2	20.2
Boltzmann's constant	k_B	dB(J/K)		-228.6
Signal-to-noise ratio	SNR	dB	18.8	17.8
Signal-to-interference-plus-noise ratio	SINR	dB	14.3	15.8
Spectral efficiency [22]	η_{se}	bit/(s · Hz)	3.2	3.5

Due to the limited number of adjacent GSO networks that significantly affect transmissions and services, the coordination arc in the K- and Ka-bands is defined as $\pm 8^\circ$, according to ITU-RR Volume II, Appendix 5, Table 5-1. This means that, for an entry into the MIFR, agreements are only required from those networks located within the defined coordination arc. Networks outside this arc must only taken into account if an administration believes that its network(s) would experience harmful interference and explicitly submits an objection at the time of the publication of the filing. As a result, the number of coordination cases for a GSO network is manageable. This, however, does not apply to coordination with terrestrial services.

1.2.3 Terrestrial and Space Services Sharing Frequency Bands

In the space-to-Earth direction, no formal coordination mechanism for satellite networks with terrestrial services exists in this frequency range. Instead, ITU-RR No. **21.16** imposes hard power flux-density (pfd) limits on satellite emissions to protect terrestrial services. These limits are necessary due to the large FOV a space station has seen from the

Table 3: Power flux-density hard limits according to Article 21.16 of the International Telecommunication Union Radio Regulations as a function of Earth station elevation for the fixed-satellite service in the 17.7-19.3 GHz frequency range, referenced to a 1 MHz bandwidth.

Frequency band	Service	Limit in dB(W/m ²) for Earth station elevations ε			Reference bandwidth
		0°-5°	5°-25°	25°-90°	
17.7-19.3 GHz	Fixed-satellite (space-to-Earth)	-115	$-105 + 0.5(\varepsilon - 5)$	-105	MHz
19.3-19.7 GHz	Fixed-satellite (space-to-Earth)	-115	$-105 + 0.5(\varepsilon - 5)$	-105	MHz

GSO. A case-by-case coordination of the space-to-Earth emissions with each receiving terrestrial station within the FOV of a GSO network would not be possible. Hence, hard limits allow the sharing of the band, ensuring robust and reliable protection of terrestrial services, which are examined by the ITU at the time of submission of the frequency application.

Table 21-4 in the ITU-RR provides the pfd hard limits as a function of the angle of arrival, respectively, elevation ε at the Earth's surface for different space services, and frequency bands. The ITU-RR limits applicable to the FSS in the 17.7-19.7 GHz frequency range are shown in Table 3. These limits are visualized in Fig. 5, complemented by the corresponding equivalent isotropically radiated power spectral-density (EIRP-SD) of a satellite in the GSO, by adding the spreading loss of the distance between the GSO and

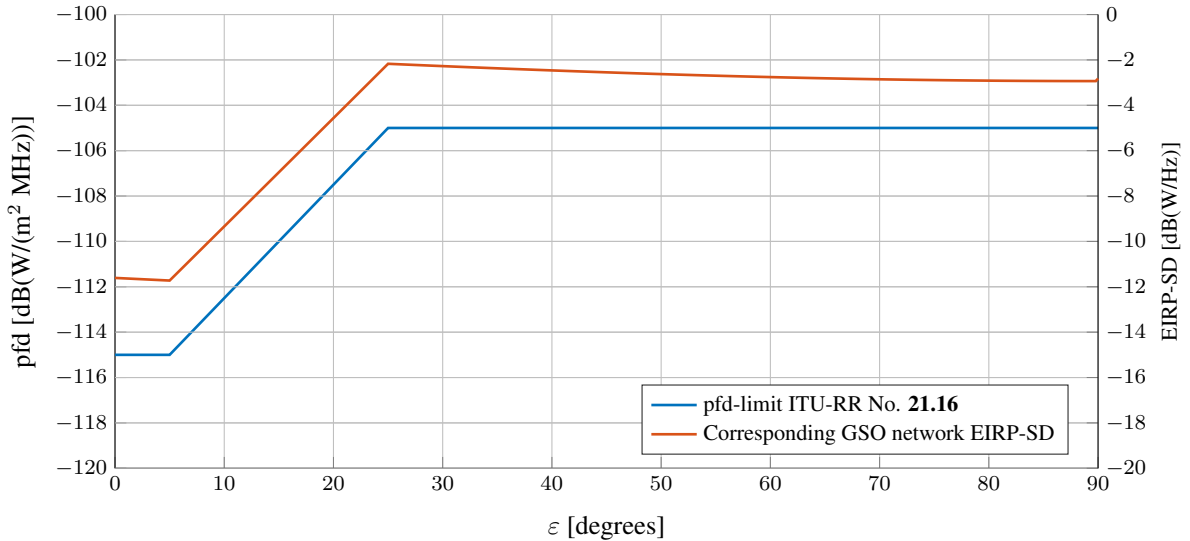


Figure 5: Limits of power flux-density from space stations to protect terrestrial stations, according to Article 21.16, Table 21-4 of the International Telecommunication Union Radio Regulations, and the corresponding maximum permissible equivalent isotropically radiated spectral power density in the geostationary satellite orbit.

a point on the Earth's surface having a particular angle of arrival:

$$\text{EIRP-SD} = \text{pfd} + 10 \log_{10}(4\pi d(\varepsilon)^2) - 10 \log_{10}(B_{\text{ref}}). \quad (1.1)$$

$d(\varepsilon)$ is the distance between the considered point on the surface of the Earth having an angle of arrival, and B_{ref} is the reference bandwidth.

A comparison of the maximum permissible EIRP-SD per Table **21-4** with the required EIRP-SD in the LBs in Table 2 shows that the hard limits for the protection would only be a limit for very high spectral efficiencies, and most of the links are not limited by this regulatory framework. The pfd limit will become dominant when low angles of arrival are served with the beam peak of a GSO beam.

The coordination requirements for Earth-to-space transmissions under the Provision of ITU-RR No. **9.14** differ from those for space-to-Earth transmissions. For transmitting satellite earth stations, coordination is required with terrestrial services, when those earth stations are located in densely populated areas where terrestrial services are active.

The procedure for coordination is outlined in Appendix 7 in Vol. II of the ITU-RR and describes the method for determining the coordination area around an earth station in frequency bands between 100 MHz and 105 GHz. The coordination area defines the region surrounding an earth station operating in the same frequency band as terrestrial services, within which the permissible interference levels may be exceeded and, consequently, coordination is required.

The area is determined based on the known characteristics of the respective earth station(s), conservative assumptions for the propagation path. Hence, coordination can be performed only on a case-by-case basis for the particular location and the technical and operational characteristics on a link basis. For moving FSS terminals on a car, train, or an aircraft, this procedure becomes obsolete and requires new regulations covered in the Res. **169 (Rev. WRC-19)**.

1.2.4 Resolution 169 (Rev. WRC-23)

The WRC-19 has made a significant Res., allowing A-ESIMs to utilize the K- and Ka-band spectrum allocated to the FSS on a primary basis. This spectrum, also allocated to terrestrial services on a primary basis, is now open for A-ESIMs communication with GSO networks.

The regulatory provisions in Res. **169 (Rev. WRC-23)** oblige GSO FSS satellite operators to accept interference and not claim protection from other incumbent services despite operating under the primary allocation of the FSS. Using the FSS spectrum for applications employing a mobile nature, e.g., the connection of aircraft, trains, ships, or cars, represents a break with the existing regulations, rules, and procedures. Especially for A-ESIM, the coordination process for the Earth-to-space emissions on a case-by-case

basis is impracticable, as operators would be obliged to coordinate all of their A-ESIM terminals with all stations of terrestrial services in the anticipated service area. Effectively, this would be the surface of the Earth, visible from the associated GSO location(s).

In the absence of a practicable coordination procedure of ESIMs with stations of terrestrial services, Res. **169 (Rev. WRC-23)** resolved that ESIMs could use the FSS spectrum in the 17.7-19.7 GHz (space-to-Earth) and 27.5-29.5 GHz (Earth-to-space) frequency range under multiple conditions, from which the most important ones are listed hereafter:

- The ESIM characteristics shall remain within the envelope characteristics of typical earth stations associated with the GSO satellite network.
- The use of ESIMs shall not cause more interference and shall not claim more protection than for typical earth stations in this GSO FSS network.
- The operation of ESIMs shall comply with the coordination agreements for the frequency assignments of the typical earth station of this GSO FSS network obtained under the relevant provisions of the Radio Regulations;
- ESIMs in the frequency band 17.7-19.7 GHz shall not claim protection from terrestrial services;
- Transmitting aeronautical and maritime ESIMs in the frequency band 27.5-29.5 GHz shall not cause unacceptable interference to terrestrial services.
- Transmitting land ESIMs in the frequency band 27.5-29.5 GHz shall not cause unacceptable interference to terrestrial services in neighboring countries.
- ESIMs shall not claim protection from non-GSO FSS systems operating in the frequency band 17.8-18.6 GHz.
- ESIMs shall not claim protection from broadcasting-satellite service feeder-link earth stations operating in the frequency band 17.7-18.4 GHz.

Those resolves were necessary, as a mobile earth station uses the spectrum allocated to FSS and is thus unable to apply the coordination procedures concerning No. **9.14**. Due to the impractical and nearly impossible case-by-case coordination, an overall approach was required. The protection of the terrestrial services in 27.5-29.5 GHz is now ensured by EIRP hard limits for land mobile and maritime ESIMs. These hard limits are set to control the maximum power that can be transmitted by ESIMs, thereby preventing harmful interference with terrestrial services. For A-ESIMs, pfd hard limits on the Earth's surface ensure protection to terrestrial services, even separated in different limits depending on the flight altitude of the aircraft. All ESIMs are obliged not to exceed those EIRP and pfd

limits. Res. **169** was revised at WRC-23, adding procedures for examination of emission levels of A-ESIMs to ensure the protection of terrestrial radiocommunication services.

The acceptance of RFI caused by FS and MS transmitters in the 17.7-19.7 GHz frequency range is left for the ESIM operators to cope with. Thus, ESIM operators are responsible for managing and mitigating the interference caused by these transmitters, which is a critical aspect of their operational responsibilities. Having highly directive antennas fed with high power for communication over long distances, the FS has the highest potential for interfering with SATCOM ESIM links and is, therefore, the subject of this thesis.

Key Takeaway

Allowance of A-ESIMs to use FSS is specified in the footnotes of the Frequency Allocation Table, referencing Res. 169 Rev. (WRC-23). No formal coordination procedure exists between co-primary satellite and terrestrial services in the space-to-Earth direction. The application of probability density function (pdf) hard limits ensures the protection of terrestrial services from emissions of A-ESIM. The protection of nominal stationary FSS earth stations is achieved by coordination with stations of terrestrial services. For moving A-ESIM, coordination with stations of terrestrial service is impossible, and thus, terrestrial interference must be accepted by A-ESIMs.

1.3 Relevance in Practice

The dilemma in operating A-ESIM terminals in the K- and Ka-bands is that, while broadband IFE services require robust, high-throughput links under dynamic conditions, the regulatory framework offers no protection against interference from co-frequency terrestrial systems. As a result, uncontrolled RFI can occur at any time and location along a flight route, without warning or mitigation from the regulatory side.

In practice, this means that IFE terminals must be engineered to tolerate unknown, time-varying, and location-specific interference, directly affecting service availability. To ensure a well-experienced quality of service, system designers need to cope for variations in spectral efficiency, use larger or more complex antennas, and apply conservative link budgets. These design constraints increase costs and reduce flexible use of the spectrum.

The effect for passengers is noticeable: data rates in the aircraft are poor, services may be interrupted, and connection stability varies. Airlines often reflect this uncertainty in their service disclaimers, noting that connectivity is not guaranteed and depends on external technical and regulatory factors, as illustrated in Fig. 6.

Mitigation measures such as changing frequencies, switching satellites, or altering flight routes are associated with high operational costs and are not feasible for all airlines. The underlying issue is not purely technical but stems from legacy spectrum-sharing regulations. New applications, such as mobile broadband via satellite, must operate within these rigid frameworks, which can lead to lengthy coordination procedures and operational compromises, delaying the introduction of innovative services. In the aeronautical SATCOM context, such delays directly hinder airlines in meeting the growing passenger demand for high-quality connectivity.

This thesis does not seek to challenge **Res. 169 (Rev. WRC-23)**, but rather to highlight the difficulty it creates for the practical deployment of IFE systems. Introducing a statistical method to quantify the interference environment is a step toward reconciling system requirements with regulatory obligations.

1.4 Contribution of this Thesis

1.4.1 Summary

This thesis aims to develop a robust model for predicting the impact of time-variant FS RFI on aeronautical SATCOM receivers, particularly in the 17.7-19.7 GHz band. The following questions and research tasks are elaborated in this thesis:

- To identify and analytically describe the significant physical, technical, operational, and regulatory parameters determining FS RFI into an A-ESIM SATCOM receiver.
- To determine which elements and parameters are required to provide a simplified but representative model of the interference.
- To develop the *AERO-FS* interference model for quantifying FS RFI in aeronautical SATCOM receivers in the 17.7-19.7 GHz frequency range.
- To quantify the degradation caused by FS RFI on spectral efficiency and link performance under realistic aeronautical operational conditions.
- To derive a stochastic channel model that accurately captures the time-varying nature of FS RFI using finite-state Markov chains and clustering algorithms.

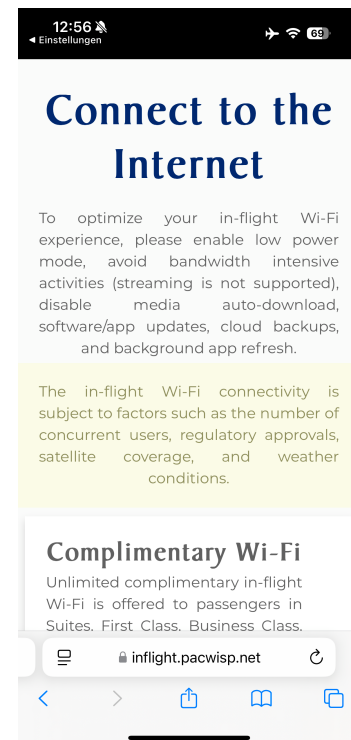


Figure 6: Screenshot of an in-flight connectivity portal on a Singapore Airlines flight, illustrating that service availability depends on both technical and regulatory factors.

- To generalize and transpose the model to different aircraft antenna diameters, center frequencies, and flight velocities.
- To specify an experimental measurement campaign to detect and quantify FS RFI in support of the developed model.

A system model for A-ESIM reception of unwanted emissions from terrestrial FS stations is developed to address these questions, identifying and assessing all influencing parameters. From this, the parameters most relevant to aggregate FS RFI are selected and characterized for a representative IFE scenario, considering operational conditions and constraints across distinct commercial flight profiles. The main task is to accurately model the behavior of aggregate FS RFI in a time-varying environment where existing models lack details or have oversimplified assumptions. The derived model generates an extensive set of empirical RFI data using exhaustive computer simulations.

Based on the geometric simulation's statistical findings, this data set of time variant power levels of FS RFI is aggregated into a stochastic model of representative FS RFI states, applying data clustering algorithms using Vector-Quantization (VQ).

The developed statistics and the stochastic model enable quick and reliable prediction of FS RFI levels and the expected performance degradation of A-ESIMs operating in the 17.7-19.7 GHz band. It supports system design and future research on interference mitigation without requiring detailed knowledge of terrestrial FS operations. The proposed system and simulation framework are generic and applicable to many aeronautical SATCOM scenarios involving spectrum sharing with FS. While absolute RFI levels depend on the specific application, frequency band, and the technical and operational characteristics of both the FS and the aircraft, the modeling approach remains widely applicable.

This thesis is structured as follows:

- Section 2 introduces the considered system model and provides a detailed analytical characterization. It then derives and discusses all relevant parameters influencing the aeronautical SATCOM channel.
- Section 3 presents the development of the *AERO-IF* interference model, including all required input parameters. The simulation results are evaluated regarding their statistical properties and impact on system performance.
- Section 4 describes transforming the empirical simulation data into a stochastic model using a finite-state Markov chain constructed via VQ. The resulting model enables a time-independent, computationally efficient estimation of FS RFI, which is suitable for system design, link planning, and developing interference mitigation strategies.

- Section 5 outlines the conceptual design of an experimental measurement campaign proposed in this thesis to detect and quantify FS RFI in the aeronautical SATCOM channel. The section details the system architecture, measurement strategy, and practical considerations for preparing the in-flight data measurement.
- Section 6 concludes the thesis by summarizing the key findings and outlining future research and development directions.

1.4.2 Publications

In the course of this thesis, the following results have been published:

- S. P. Winter, A. Bhattacharya, T. Delamotte, and A. Knopp, "Spatial Correlation of Rain Attenuation in Space-to-Earth Links," Proc. 28th International Workshop on Smart Antennas 2025, Erlangen, Germany, 2025. *Accepted paper*.
- S. P. Winter and A. Knopp, "Impact of Multipath Signals on Terrestrial Fixed Service Interference in Aeronautical SATCOM," GLOBECOM 2022 - 2022 IEEE Global Communications Conference, Rio de Janeiro, Brazil, 2022, pp. 5899-5904, doi: 10.1109/GLOBECOM48099.2022.10001111.
- S. P. Winter and A. Knopp, "Modeling of Fixed Service Interference in Aeronautical SATCOM Channels," in IEEE Transactions on Aerospace and Electronic Systems, vol. 58, no. 2, pp. 942-961, April 2022, doi: 10.1109/TAES.2021.3117088.
- S. P. Winter and A. Knopp, "Statistics of Terrestrial Fixed Service Interference in the Aeronautical SATCOM Channel," ICC 2019 - 2019 IEEE International Conference on Communications (ICC), Shanghai, China, 2019, pp. 1-7, doi: 10.1109/ICC.2019.8762036.
- S. P. Winter, M. G. Schraml, M. T. Knopp and A. Knopp, "Spatial Modulation for Improved Eavesdropping Resistance in Multi-Beam Satellite Downlinks," MILCOM 2018 - 2018 IEEE Military Communications Conference (MILCOM), line-of-sight (LOS) Angeles, CA, USA, 2018, pp. 829-834, doi: 10.1109/MILCOM.2018.8599822.
- S. P. Winter, C. A. Hofmann and A. Knopp, "Antenna diversity techniques for enhanced jamming resistance in multi-beam satellites," MILCOM 2016 - 2016 IEEE Military Communications Conference, Baltimore, MD, USA, 2016, pp. 618-623, doi: 10.1109/MILCOM.2016.7795396.
- R. T. Schwarz, S. P. Winter and A. Knopp, "MIMO application for reduced adjacent satellite interference in SATCOM downlinks," 2014 IEEE International Conference on Communications (ICC), Sydney, NSW, Australia, 2014, pp. 3570-3575, doi: 10.1109/ICC.2014.6883875.

1.4.3 Patents

In the course of this thesis, the following patent has been published:

- S. P. Winter et. al., "Satellite communications system and method for transmitting a bit stream therewith", EP 3641156A1, 18.10.2018.

2 System Characterization

This section assesses the factors and parameters contributing to terrestrial FS RFI in the aeronautical SATCOM link. It begins with an overview of the system model, outlining the scenario under investigation. Following this, the particular geometries in the air-to-ground path are determined. Based on these initial assumptions, the channel models for each propagation path are developed, assessing their contributing elements. The impact of critical parameters from each propagation element in the channel gain is then analyzed for a single-entry interference case, providing a comprehensive analysis of its contributions. Finally, a summary of all relevant parameters is provided and associated with deciding whether the particular effect needs to be considered in the *AERO-FS* interference model.

2.1 The Interfering System Model

The contemplated system model to assess aggregate FS RFI consists of three main elements: the terrestrial layer with the technical characteristics of the FS stations, the aeronautical layer comprising the aircraft characteristics concerning the SATCOM receiver, and the propagation between both. The developed channel model covers the characteristics and interaction between the terrestrial and the aeronautical layers.

Fig. 7 shows the considered system model in a local reference system used to analytically describe the aggregate terrestrial FS RFI in an aeronautical broadband SATCOM channel for an A-ESIM receiver. While the appearing interference environment includes

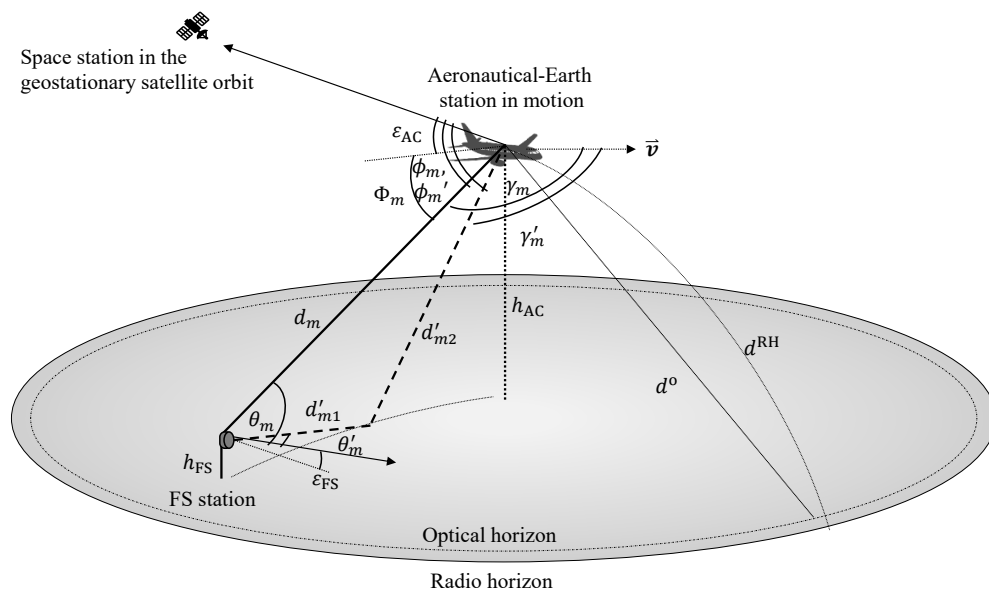


Figure 7: System model of an aircraft flying along a great-circle path, with a single satellite communications antenna pointed toward a fixed location on the geostationary orbit arc, receiving interfering signals from terrestrial fixed service stations.

multiple interfering sources, the shown system model is limited to a single-entry interference case of one FS station for simplicity. The model considers a spherical, plain Earth model with a single aircraft flying at a cruising altitude h_{AC} above ground level at a constant ground speed of v_{AC} . The aircraft's velocity vector $\vec{v} \in \mathbb{R}^3$ represents the flight direction, respectively the aircraft's heading. The aircraft operates as an A-ESIM inside the coverage of a GSO FSS network, receiving signals from the GSO space station in the frequency range of 17.7-19.7 GHz. The A-ESIM SATCOM antenna boresight points toward the GSO satellite at the orbit location Lon_{GSO} . The elevation of the aircraft's SATCOM antenna relative to the horizontal plane is denoted by ε_{AC} .

The aircraft receives wanted signals x , from the GSO network containing symbols in complex baseband notation, which are arbitrarily chosen from a symbol alphabet $\mathbb{S}$ with equal probability of occurrence. Simultaneously, the aircraft is exposed to unwanted RFI signals from a finite number of M terrestrial FS stations inside the radio horizon (RH) d^{RH} of the aircraft receiver. Each FS antenna, as part of a point-to-point or point-to-multi-point network, is mounted above the ground at a height of h_{FS} . The pointing angles of that antenna in terms of azimuth Λ_{FS} and elevation ε_{FS} define the direction of the respective FS antenna boresight. The RFI signals of the m th out of M FS stations are transmitted with an off-axis antenna gain g_{FS} of the FS antenna at the spatial angle between the respective FS station antenna pointing vector and the aircraft, denoted by θ_m .

The unwanted emissions of the respective m th FS station propagate on multiple paths to the A-ESIM receiver. The LOS component propagates on a path with distance d_m . The multipath components (MPCs), caused by reflections at the Earth's surface, propagate along indirect paths d' , and their corresponding spatial angles θ'_m , respectively. Those distances of reflection paths are denoted in Fig. 7 by the variables d'_{m1} and d'_{m2} . The off-axis discrimination of the SATCOM antenna mounted on the aircraft attenuates the FS RFI signals from the m th FS station. The spatial off-axis angle for the antenna discrimination accounting for antenna discrimination of the LOS component is denoted by ϕ_m and ϕ'_m for the angular separation of the MPCs, respectively.

Additionally, the attenuation of the aircraft fuselage is defined by the spatial angles Φ_m and Φ'_m below the horizontal plane of the aircraft. As the aircraft moves with velocity v_{AC} , a Doppler shift is introduced in the FS RFI. This Doppler shift is influenced by the spatial angle γ_m between the aircraft velocity vector $\vec{v}$ and the vector from the A-ESIM towards the m th FS station.

Let y be the received signal, comprising the wanted and unwanted signals from a finite number of M FS stations, then $y(t)$ calculates the received signals at observation time t in complex baseband notation as

$$y(t) = \underbrace{\int_{-\infty}^{+\infty} h(\dot{t}, t) x(\dot{t}) d\dot{t}}_{\text{wanted signals from the GSO satellite}} + \underbrace{\eta(t)}_{\text{receive noise}} + \underbrace{\sum_{m=1}^{M(t)} \int_{-\infty}^{+\infty} \tilde{h}_m(\dot{t}, t) \tilde{x}_m(\dot{t}) d\dot{t}}_{\text{unwanted signals from terrestrial FS}}. \quad (2.1)$$

In this thesis, the unwanted signals are assessed. For considering the unwanted interfering elements $\tilde{y}(t)$ of the receive signals only, (2.1) is simplified to

$$\tilde{y}(t) = \sum_{m=1}^{M(t)} \int_{-\infty}^{+\infty} \tilde{h}_m(\dot{t}, t) \tilde{x}_m(\dot{t}) d\dot{t}. \quad (2.2)$$

In (2.2), $\tilde{h}_m(\dot{t}, t)$ is the complex channel impulse response between the aircraft and the m th interfering FS station out of a total of M stations. The transmitted signals of the m th interfering source at excitation time $\dot{t}$ are denoted by $\tilde{x}_m(\dot{t})$. The transmit symbols for the interfering signals $\tilde{x}_m$ contain symbols in complex baseband notation, which are arbitrarily chosen from a symbol alphabet $\tilde{\mathbb{S}}$ by each FS station having equal probability of occurrence. In assuming a finite number of N propagation paths for each m th interfering FS station with discrete delays $\tau_{d_1}, \tau_{d_2}, \dots, \tau_{d_N}$, the complex channel impulse response of the m th FS station can be expressed by

$$\tilde{h}_m(\dot{t}, t) = \sum_{n=1}^N a_n(t) e^{j(\Delta\varphi_n(t) + \Delta\omega_n(t - \dot{t} - \tau_{d_n}))} \delta(t - \dot{t} - \tau_{d_n}). \quad (2.3)$$

The complex parameters $a_n(t) e^{j(\Delta\varphi_n(t) + \Delta\omega_n(t - \dot{t} - \tau_{d_n}))}$ describe the variations in amplitude and phase over time for the different propagation paths. The channel gain a_n represents a combination of gains and losses along each path, subject to specific physical effects, technical and operational characteristics of the FS station and the aircraft, and the Earth's surface and surrounding infrastructure or vegetation. $\Delta\varphi_n(t) = 2\pi\Delta d_n(t)/\lambda$ denotes the phase difference of each propagation path, and $\Delta\omega_n(t - \dot{t} - \tau_{d_n})$ accounts for the Doppler shift applied to the signal after it has been delayed on the signal path. The delay τ_{d_n} on the n th out of N paths is calculated as $\tau_{d_n} = d_n(t)/c_0$, where $c_0 = 299\,792\,458$ m/s is the speed of light in Vacuum. Finally, the Dirac delta function in (2.3) is denoted by δ . For each single-entry interference case, the different propagation paths are categorized into three main types of contributions:

- a direct LOS component,
- a coherent/specular (co) reflected component,
- and a finite number of V non-coherent/diffuse (nco) components.

Thus, $N = \text{LOS} + \text{co} + V \cdot \text{nco}$. The three different propagation elements are described in more detail in their complex channel impulse responses in (2.4).

$$\begin{aligned} \tilde{h}_m(\dot{t}, t) = & |a^{\text{LOS}}(t)| e^{j(\Delta\varphi^{\text{LOS}}(t) + \Delta\omega^{\text{LOS}}(t - \dot{t} - \tau_d^{\text{LOS}}))} \delta(t - \dot{t} - \tau_d^{\text{LOS}}) \\ & + |a^{\text{co}}(t)| e^{j(\Delta\varphi^{\text{co}}(t) + \Delta\omega^{\text{co}}(t - \dot{t} - \tau_d^{\text{co}}))} \delta(t - \dot{t} - \tau_d^{\text{co}}) \\ & + \sum_{v=1}^V |a_v^{\text{nco}}(t)| e^{j(\Delta\varphi_v^{\text{nco}}(t) + \Delta\omega_v^{\text{nco}}(t - \dot{t} - \tau_{dv}^{\text{nco}}))} \delta(t - \dot{t} - \tau_{dv}^{\text{nco}}) \end{aligned} \quad (2.4)$$

The geometric relationships between the FS stations and the victim aircraft determine the respective channel gains a^{LOS} , a^{co} and a^{nco} of each component. These gains incorporate all gains and losses along the signal paths between an interfering FS station and the aircraft receiver and are assessed in detail in section 2.3.

Classic fading models such as Rayleigh and Rician distributions are widely used in mobile radio to statistically characterize multipath propagation. It is questionable if one of those well-established models can be applied in the modeling of the FS RFI.

The Rayleigh model assumes a completely diffuse multipath environment without a dominant LOS path. In contrast, the Rician model includes a dominant LOS component along with diffuse scattering. While the Rician K -factor captures the power ratio between LOS and multipath, the LOS component is typically assumed to be constant or deterministic over time. It is yet to be determined whether those existing models can be used to model the aggregate FS RFI, or if new distributions need to be applied.

Key Takeaway

The FS RFI channel can be decomposed into deterministic and stochastic contributions from LOS, specular, and diffuse multipath components, forming the basis for a detailed channel gain analysis associated with LOS, coherent, and non-coherent reflections. Whether conventional stochastic models, such as Rayleigh or Rician fading, are applicable for the aggregate modelling of multiple interference sources remains to be determined.

2.2 The Air-to-Ground Path

Quantifying the channel gains of each propagation component requires the accurate modeling of the pertaining slant path geometries. This section outlines the methodology for these calculations, based on the Recs. ITU-R P.453 [23], and ITU-R P.528 [24] and its detailing in Report ITU-R P.2345-2 [25]. Those Recommendations and Reports provide guidelines for modeling the effects of atmospheric refractivity on radio propagation for both the LOS and indirect slant paths, accounting for the impact of the Earth’s curvature and varying atmospheric refractivity profiles.

2.2.1 Aeronautical Geometries

Fig. 8 depicts the main elements of a single-entry configuration, which are required to determine the air-to-ground geometries. Of main interest are the number of interfering FS stations M , their refracted slant path distances d, d' , and the grazing angles θ_g for the reflection path geometries, in particular, the incident and scattered angles θ_i and θ_s .

As seen from the aircraft the number of visible FS stations is defined by the radio horizon d^{RH} . When the refracted distance d^r from the aircraft to the m th FS station is smaller than the radio horizon, i.e., $d^r < d^{\text{RH}}$, it could potentially interfere with the aircraft receiver, depending on whether the FS station exhibits frequency overlap. The radio horizon depends on the flight altitude of the aircraft h_{AC} , and the antenna height of the FS station h_{FS} above ground. Generically, the distance of the refracted path of a radio wave

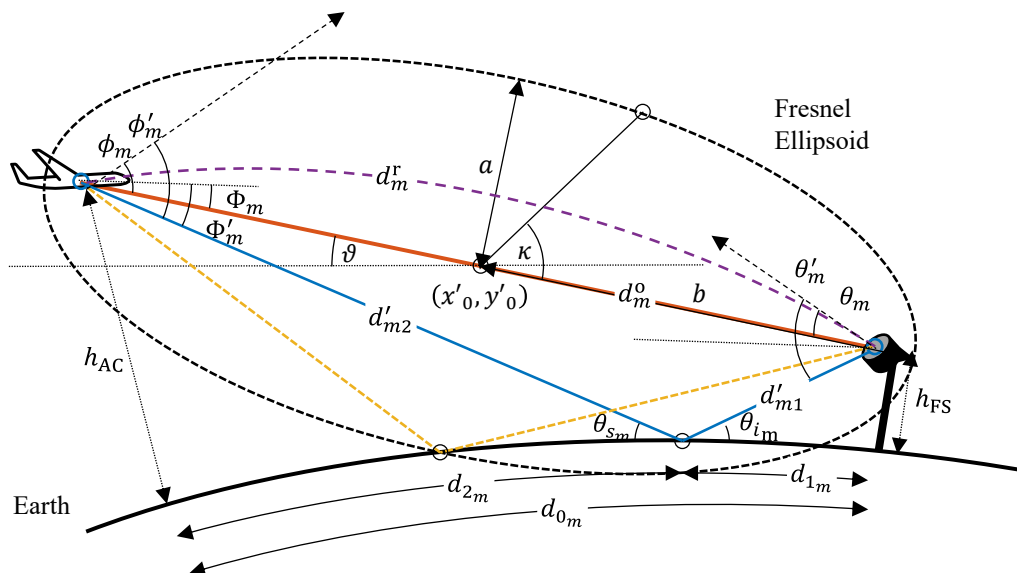


Figure 8: Spherical, plane-Earth model with parameter labeling for the aeronautical reflection geometries in a single-entry interference case, showing the line-of-sight as well as the specular and diffuse reflection paths.

is calculated from the optical distance d^o by

$$d^r = \sqrt{2k_e d^o (r_E + h)}, \quad (2.5)$$

where r_E is the radius of the Earth, which is defined in Rec. ITU-R S.1503-4 [26] by $r_E = 6\,378.145$ km and h is the altitude above the surface of the Earth. k_e is the effective earth radius factor. It is a function of the flight altitude and can be calculated from [23] and [27]. According to (3) in [27], the effective radius of the Earth is $r_{\text{eff}} = k_e r_E$, where k_e is the effective Earth radius factor, with:

$$\frac{1}{r_{\text{eff}}} = \frac{1}{k_e r_E} = \frac{1}{r_E} + \frac{\partial n}{\partial h}, \quad (2.6)$$

where n is the refractive index of the atmosphere. Solving (2.6) for k_e gives

$$k_e = \frac{1}{1 + r_E \frac{\partial n}{\partial h}}. \quad (2.7)$$

The refractive index n as a function of height $h = \{h_{\text{AC}}, h_{\text{FS}}\}$ as provided in [23] is expressed generically by an exponential law

$$n(h) = 1 + N_0 \cdot 10^{-6} e^{-\frac{h}{h_0}}. \quad (2.8)$$

$N_0 = 315$ in N -Units is the average global mean value of atmospheric refractivity extrapolated to sea level and the parameter $h_0 = 7.35$ km is the scale height. Calculating the derivative of n in (2.8) with respect to h ,

$$\begin{aligned} \frac{\partial n}{\partial h} &= \frac{\partial}{\partial h} \left(1 + N_0 \cdot 10^{-6} e^{-\frac{h}{h_0}} \right) \\ &= N_0 \cdot 10^{-6} \frac{\partial}{\partial h} \left(e^{-\frac{h}{h_0}} \right) \\ &= N_0 \cdot 10^{-6} \left(-\frac{1}{h_0} \right) \left(e^{-\frac{h}{h_0}} \right) \end{aligned} \quad (2.9)$$

putting it into (2.7), and solving it for k_e leads to the following equation for the Earth refractivity factor k_e :

$$k_e(h) = \frac{1}{1 - r_E \frac{N_0}{h_0} 10^{-6} e^{-\frac{h}{h_0}}}. \quad (2.10)$$

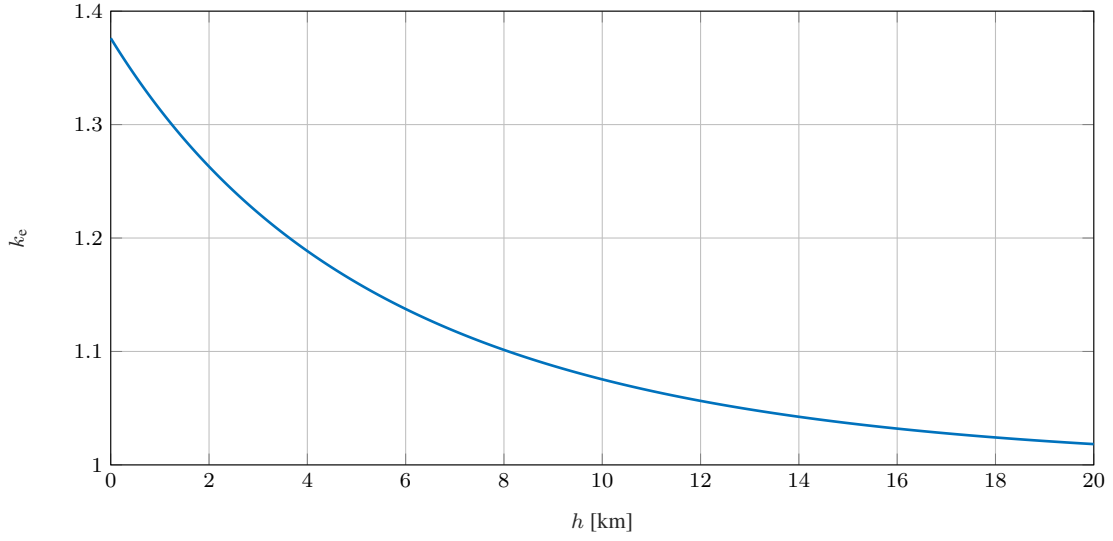


Figure 9: Dimensionless effective Earth radius factor k_e as a function of altitude, demonstrating that refractivity is high at low altitudes, where the effective Earth radius is about 1.4 times larger, while at higher altitudes k_e is close to 1 and can be considered negligible.

The effective Earth radius factor k_e is dimensionless. Its dependency as a function from h is depicted in Fig. 9, showing that it is mainly an effect to be considered at lower altitudes.

The optical distance d^o is calculated using the law of cosines and having knowledge about the distance d_{0_m} between the m th FS station and the aircraft on the surface of the Earth, by

$$d^o = \sqrt{(r_E + h_{FS})^2 + (r_E + h_{AC})^2 - 2(r_E + h_{FS})(r_E + h_{AC}) \cos\left(\frac{d_{0_m}}{r_E}\right)}. \quad (2.11)$$

For both the coherent and non-coherent reflection geometries, the respective optical slant path distances can be calculated similarly to (2.11), based on the distances of the incident and scattered path on the surface of the Earth.

$$d'_{m2} = \sqrt{r_E^2 + (r_E + h_{AC})^2 - 2r_E(r_E + h_{AC}) \cos\left(\frac{d_{2_m}}{r_E}\right)}, \quad (2.12)$$

respectively,

$$d'_{m1} = \sqrt{r_E^2 + (r_E + h_{FS})^2 - 2r_E(r_E + h_{FS}) \cos\left(\frac{d_{1_m}}{r_E}\right)}. \quad (2.13)$$

In the following sections of this thesis, the distances for all slant paths d , d' are the refracted slat paths d^r calculated from the optical distance according to (2.5).

The grazing angles θ_{im} , θ_{sm} are calculated from the law of cosines, too.

$$\theta_{im} = \cos^{-1} \left(\frac{r_E^2 + d'_{m1}{}^2 - (r_E + h_{FS})^2}{2r_E d'_{m1}} \right), \quad (2.14)$$

and for the scattered angle

$$\theta_{sm} = \cos^{-1} \left(\frac{r_E^2 + d'_{m2}{}^2 - (r_E + h_{AC})^2}{2r_E d'_{m2}} \right). \quad (2.15)$$

In case of the specular reflection $\theta_{im} = \theta_{sm} = \theta_{gm}$ the determination of the geometries is not easy as an exact solution exists only for a flat Earth model. Boithias provided in [28] an approximate solution for small angular distances for terminals near the surface of the Earth. It requires two intermediate values which are calculated, adapted to the FS RFI interference case and nomenclature in Fig. 8, by

$$l = \frac{d_{0m}^2}{4r_{\text{eff}}(h_{AC} + h_{FS})}, \quad (2.16)$$

$$c = \frac{(h_{AC} - h_{FS})}{(h_{AC} + h_{FS})}, \text{ and} \quad (2.17)$$

$$b = 2\sqrt{\frac{l+1}{3l}} \cdot \cos \left[\frac{\pi}{3} + \frac{1}{3} \cos^{-1} \left(\frac{3c}{2} \sqrt{\frac{3l}{(l+1)^3}} \right) \right]. \quad (2.18)$$

The path lengths d'_{m1} and d'_{m2} , the path difference between reflected path and the LOS path $\Delta\varphi_m$, as well as the grazing angles θ_g are then given by:

$$d_{1m} = \frac{d_{0m}}{2} (1 + b). \quad (2.19)$$

Putting (2.19) into (2.13) allows for the calculation of the phase difference

$$\Delta\varphi_m = \frac{2\pi}{\lambda} (d'_{m1} + d'_{m2} - d_m). \quad (2.20)$$

Finally, the grazing angle is calculated by

$$\theta_g = \frac{h_{AC} + h_{FS}}{d_{0m}} [1 - l(1 + b^2)]. \quad (2.21)$$

The spatial angles to calculate the off-axis discrimination between the respective antenna boresights and the direction to the aircraft / FS stations, as well as the angles for the fuselage attenuation and the Doppler shifts, are based on vector geometry and their determination are discussed in section 3.

2.2.2 Multipath Geometries

Rummler et. al. showed in [29] that multipath fading of LOS radio relay could occur under specific atmospheric conditions. In particular, a ground reflection could fade the entire signal bandwidth due to its short excess delays compared to the LOS path. Depending on the fading depth, diffuse MPCs would then become dominant. Fading of the FS RFI signals would be beneficial for the aircraft receiver. They would reduce the interference level and temporarily improve the SINR temporary, depending on the time those particular geometries appear.

Hence, for the reflected contributions, it is desirable to determine the geometric conditions under which the path difference between the reflected and the LOS paths differ in the phase of $\lambda/2$ or multiples of $\lambda/2$. In that case, the LOS and the reflected FS RFI signals add up destructively, reducing the interference. Drawing the Fresnel ellipses with the aircraft and the FS station in the respective foci determines these geometric conditions where the phase difference results in deconstructive addition. Using the nomenclature for a rotated Fresnel ellipsoid positioned between an aircraft and an FS station introduced in Fig. 8, the 1st Fresnel ellipse in parametric form with the parameter $\kappa \in [0, 2\pi]$ and center coordinates x_0 and y_0 can be written as:

$$\begin{aligned} x(\kappa) &= x_0 + a \cdot \cos(\kappa) \cdot \cos(\vartheta) - b \cdot \sin(\kappa) \cdot \sin(\vartheta) \\ y(\kappa) &= y_0 + a \cdot \sin(\kappa) \cdot \sin(\vartheta) + b \cdot \sin(\kappa) \cdot \cos(\vartheta) \end{aligned} \quad (2.22)$$

$a = d/2 + \lambda/4$ and $b = \sqrt{a^2 - (d/2)^2}$ are the semi-major and semi-minor axes of the ellipse. The angle ϑ is the rotation angle of the ellipse with respect to the center coordinates, which corresponds to the spherical angle between the aircraft and the horizontal plane, as seen from the FS station antenna.

Fig. 10 plots the 1st Fresnel ellipsoids according to (2.22) using a local East, North, Up (ENU) reference system having its origin in the base of the FS station on the surface of the Earth and describing the E-coordinate as the x-axis and the U-coordinate as the y-axis. The distances between the FS station and the aircraft result in different rotation angles ϑ , and semi-major and -minor axes of the respective Fresnel ellipsoid. Fig. 10 shows multiple distances where the ellipses touch or intersect the surface of the Earth, i.e., $U = 0$ km. No such cases exist for shorter distances, respectively, with larger rotation angles $\vartheta \geq 20^\circ$, depending on the selected FS antenna height and the flight altitude.

The intersections of the ellipse function with the surface of the Earth have multiple degrees of freedom, such as h_{FS} , h_{AC} , f , d^0 , and the phase difference $\Delta\varphi$, which are multiples of $\lambda/2$. Therefore, the Fresnel ellipsoid is not fixed and cases where fading eliminates the FS RFI can occur, but only for certain geometric conditions, as the rotation angle ϑ of the Fresnel ellipse as well as the shape (a, b) of the ellipse is time variant.

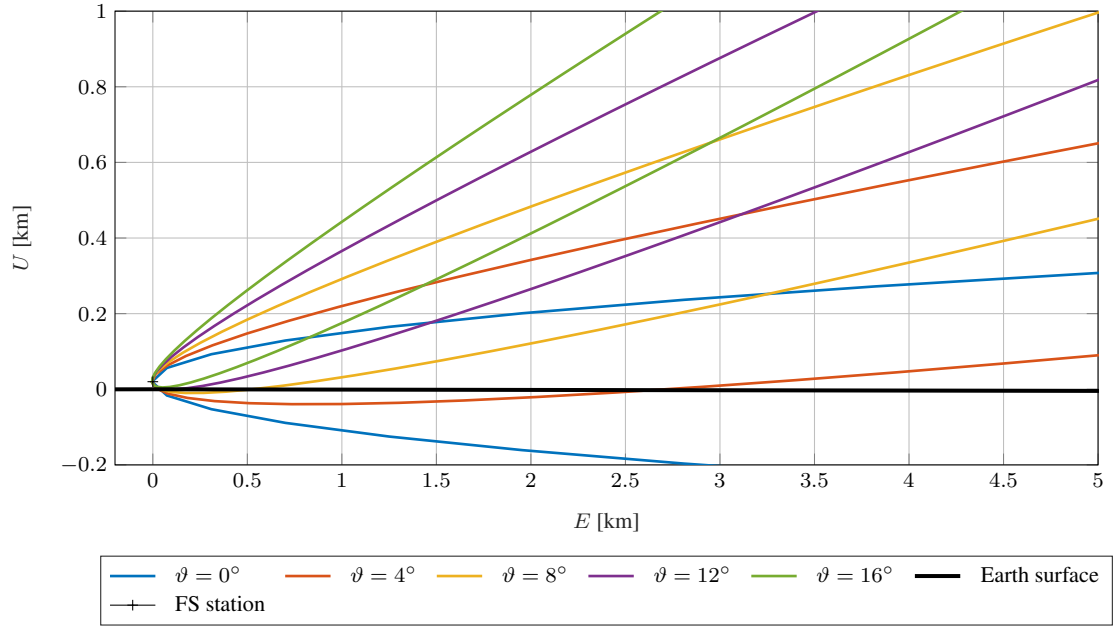


Figure 10: First Fresnel ellipsoids for different angles of arrival ϑ at the fixed service station, assuming a conservative fixed service station antenna height of $h_{\text{FS}} = 20$ m and an aircraft flight altitude of $h_{\text{AC}} = 5$ km.

The amount of deconstructive addition also depends on the reflection coefficient at the reflection point, determined by the occurring surface. This amount of energy being reflected from the Earth's surface depends on the surface's roughness and electrical characteristics at the reflection point. Lord Rayleigh analyzed the impact of the roughness of a surface. The Rayleigh surface roughness criterion considers the incidence wave's wavelength and incident angle. A surface can be considered rough if the phase difference between two rays, which are reflected from a surface with the same incident and scattering angle, is larger than $\pi/2$ and would interfere destructively. The critical height h_c to determine whether a considered surface is rough can be calculated with [30]

$$h_c < \frac{\lambda}{8 \cos \theta_i}. \quad (2.23)$$

In the considered scenario, at an frequency of $f = 18$ GHz and for angles of the incident wave $\theta_i \in [0, 80]$, the height difference h_c must be below 1 cm to be considered as smooth. Hence, it can be assumed the surface of the spherical Earth model to be rough for incidence angles lower than 80 degrees. The major impact on the scattered energy has the Fresnel reflection coefficient for the pertaining polarization. It is defined in Rec. ITU-R P.682 for linear polarization.

$$\Gamma_{\text{hh}}(\theta_i) = \frac{\sin \theta_i - \sqrt{\varepsilon_r - \cos^2 \theta_i}}{\sin \theta_i + \sqrt{\varepsilon_r - \cos^2 \theta_i}} \quad (2.24)$$

and

$$\Gamma_{vv}(\theta_i) = \frac{\varepsilon_r \sin \theta_i - \sqrt{\varepsilon_r - \cos^2 \theta_i}}{\varepsilon_r \sin \theta_i + \sqrt{\varepsilon_r - \cos^2 \theta_i}}. \quad (2.25)$$

The aircraft is operating in that frequency band at circular polarization to avoid depolarization loss caused by its movement. Terrestrial FS stations operate according to Rec. ITU-R F.758-7 [31] in linear polarization. The reflection from vertically polarized waves into a circularly polarized receiver (left or right hand circular polarization) is then calculated by [32]

$$\Gamma_{cv}(\theta_i) = \frac{1}{\sqrt{2}} \Gamma_{vv}(\theta_i), \quad (2.26)$$

whereas Γ for horizontal polarized waves into right hand circular polarized receivers is calculated by

$$\Gamma_{Rh}(\theta_i) = \frac{j}{\sqrt{2}} \Gamma_{hh}(\theta_i). \quad (2.27)$$

Γ for left hand circular polarized receivers is calculated by

$$\Gamma_{Lh}(\theta_i) = \frac{-j}{\sqrt{2}} \Gamma_{hh}(\theta_i), \quad (2.28)$$

respectively. The complex relative permittivity of the material at the Earth's surface denoted by ε_r in (2.24) and (2.25), is calculated by the method provided in Rec. ITU-R P.527 [33] for vegetation above freezing temperatures.

$$\varepsilon_r = \varepsilon'_v - j\varepsilon''_v, \quad (2.29)$$

where

$$\begin{aligned} \varepsilon'_v = \varepsilon_{dv} + v_{fw} & \left[\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_1}{1 + (f/f_1)^2} + \frac{\varepsilon_1 - \varepsilon_\infty}{1 + (f/f_2)^2} \right] \\ & + v_{bw} \left[2.9 + \frac{55(1 + \sqrt{f/0.02f_1})}{1 + 2\sqrt{f/0.02f_1} + (f/0.01f_1)} \right], \end{aligned} \quad (2.30)$$

and

$$\begin{aligned} \varepsilon''_v = v_{fw} & \left[\frac{(f/f_1)(\varepsilon_s - \varepsilon_1)}{1 + (f/f_1)^2} + \frac{(f/f_2)(\varepsilon_1 - \varepsilon_\infty)}{1 + (f/f_2)^2} + \frac{22.86}{f} \right] \\ & + v_{bw} \left[\frac{55(1 + \sqrt{f/0.02f_1})}{1 + 2\sqrt{f/0.02f_1} + (f/0.01f_1)} \right]. \end{aligned} \quad (2.31)$$

ε_{dv} is the real part of the relative permittivity of bulk vegetation, v_{fw} is the free water

volume fraction, and v_{bw} is the bound water volume fraction:

$$\varepsilon_{\text{dv}} = 1.7 - 0.74M_g + 6.16M_g^2, \quad (2.32)$$

$$v_{\text{fw}} = M_g(0.55M_g - 0.076), \quad (2.33)$$

$$v_{\text{bw}} = 4.64M_g^2(1 - 7.36M_g^2), \quad (2.34)$$

where M_g is the vegetation gravimetric water content, which is the weight of the moist vegetation. M_g is typically between 0.0 and 0.7.

$$\varepsilon_s = 77.66 + 103.3\Theta, \quad (2.35)$$

$$\varepsilon_1 = 0.0671\varepsilon_s, \quad (2.36)$$

$$\varepsilon_\infty = 3.52 - 7.52\Theta, \quad (2.37)$$

and

$$\Theta = \frac{300}{T + 273.15} - 1, \quad (2.38)$$

with T as the temperature in degrees Celsius. f_1 and f_2 are the Debye relaxation frequencies:

$$f_1 = 20.20 - 146.4\Theta + 316\Theta^2 \quad (2.39)$$

$$f_2 = 39.8f_1. \quad (2.40)$$

With those formulas the direct path as well as the reflected paths from various reflections, angles, temperatures and moisture can be modeled in the channel model of the particular contributions elaborated on in the following sections.

Key Takeaway

The air-to-ground path is a well-known radio communication channel whose geometries are described in the literature. ITU-R Recs. P.453, P.528, and Report P.2345 provide sophisticated models for the analytical description of the refracted and reflected propagation path geometries. The resulting expressions precisely quantify slant path distances and grazing angles for LOS and MPCs.

2.3 Channel Models

A variety of physical phenomena, technical and operational characteristics, and regulatory constraints affect the aggregate terrestrial FS RFI model in the aeronautical SATCOM channel. This section derives an analytical expression for the channel gain and systematically assesses the impact of individual parameters. Emphasis is placed on identifying the most influential factors to be considered in the subsequent simulation framework.

2.3.1 Line-of-Sight Component

The FS RFI is a sum signal of multiple fixed interference sources, a function of the changing geometry between the FS stations and the aircraft. The channel gain $a_m^{\text{LOS}}(t)$ combines various elements along the signal path, each time-variant and subject to physical effects and technical and operational characteristics. The channel gain is influenced by many degrees of freedom with varying levels of impact. For a single-entry interference path between the m th FS station and the aircraft receiver, the channel gain is computed as

$$a_m^{\text{LOS}} = \frac{g_{\text{FS}_m}(\theta_m(t))g_{\text{AC}_m}(\phi_m(t))}{a_{\text{L}_m}(d_m(t))a_{\text{F}_m}(\Phi_m(t))a_{\text{T}_m}(t)a_{\text{P}_m}(t)}. \quad (2.41)$$

In (2.41), the antenna gain of the m th FS station in the direction of the aircraft is denoted by $g_{\text{FS}_m}(\theta_m(t))$ and the antenna gain of the aircraft toward the m th visible FS station is denoted as $g_{\text{AC}_m}(\phi_m(t))$. The path loss $a_{\text{L}_m}(d_m(t))$ between the m th FS station and the aircraft, based on the free space wave propagation model, is given by [34]:

$$a_{\text{L}_m}(d_m(t)) = \frac{4\pi d_m(t)}{\lambda} \quad (2.42)$$

$a_{\text{F}_m}(\Phi_m(t))$ denotes the fuselage attenuation of the aircraft in the direction of the m th FS station. The total propagation loss along the path d_m is denoted by $a_{\text{T}_m}(t)$. Additionally, $a_{\text{P}_m}(t)$ represents the transmit polarization plane of the FS antenna and the receive polarization plane of the aircraft SATCOM antenna. A graphical representation of the received single-entry FS interference power in the LOS channel (2.41) is depicted in Fig. 11.

Here, and for all other single-entry calculations performed in this section, a reference scenario is defined to allow for comparison. It shows a worst-case analysis for an aircraft flight at an altitude of $h_{\text{AC}} = 10$ km over a single FS station, aligning the directions of the main beams of the aircraft and FS antennas to achieve the highest channel gain. The aircraft antenna is considered to have a constant elevation of $\varepsilon_{\text{AC}} = 15$ degrees.

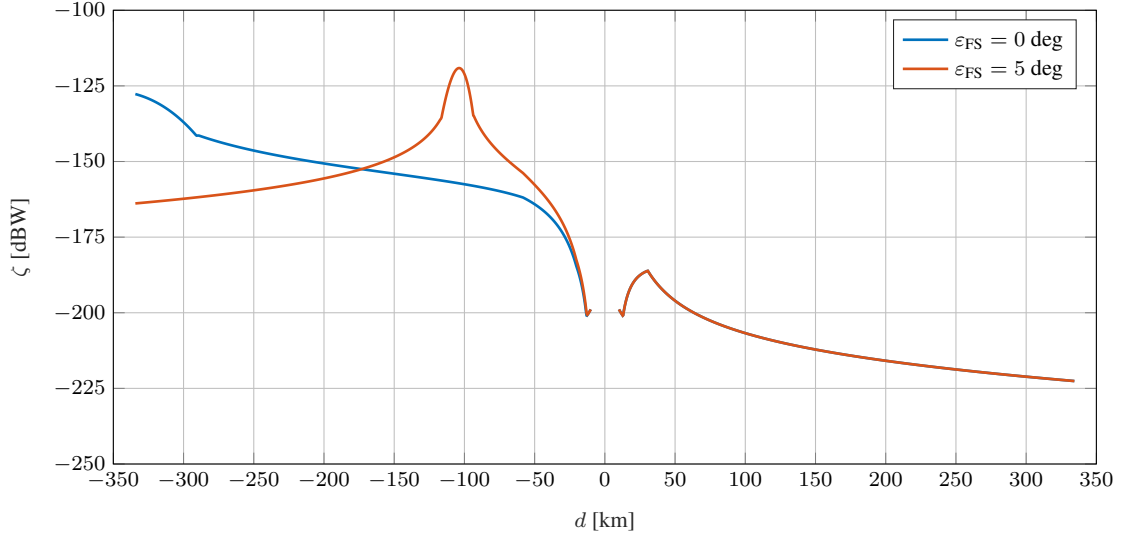


Figure 11: Fixed service line-of-sight radio frequency interference power ζ for two fixed service station antenna elevations, shown as a function of the distance d between the aircraft and the fixed service station.

The interfering FS station in this scenario is considered to have an antenna height of $h_{\text{FS}} = 0.1$ km and an antenna diameter of $D_{\text{FS}} = 2$ m. The effective transmit power p^{I} of the FS station is considered to be $p^{\text{I}} = 0.5$ W according to [31] and a^{LOS} is the channel gain of the interfering LOS component defined in (2.41).

The received FS interference power ζ is calculated for discrete distances $[d]$ by:

$$\zeta[d] = p^{\text{I}}(|a^{\text{LOS}}|[d])^2. \quad (2.43)$$

Finally, ζ is plotted for two typical FS antenna elevations of $\varepsilon_{\text{FS}} = \{0, 5\}$, representing the upper and lower bound of FS deployment and resulting geometries.

The course of ζ in Fig. 11 shows that the FS antenna gain pattern is the dominant factor influencing the channel gain of the LOS path. The highest values of ζ do not occur at the closest point between the aircraft and the FS station (i.e., directly above the FS station), but when the aircraft crosses the main beam of the FS antenna. Depending on the elevation of the FS station, the maximum ζ during a fly-over, corresponding to the beam peak of the FS antenna, occurs at the radio horizon. The maximum of ζ varies with the FS antenna elevation. At higher ε_{FS} the maximum is at shorter distances. Here, the maximum antenna gain combined with a reduced free-space path loss causes higher interference values. The gap in the curves results from the chosen x-axis representation of the distance d : at a flight altitude of $h_{\text{AC}} = 10$ km, the distance cannot be smaller than h_{AC} , i.e., $d \geq h_{\text{AC}} \quad \forall d$.

2.3.2 Specular Reflection Component

A classic two-ray path loss model simulates the specular reflection component. It superimposes the LOS signal with a delayed / reflected copy. It is commonly used to determine fading events [29]. At the specular reflection point, coherent scattering would occur and would cause the highest reflected energy. Depending on the phase difference between the LOS and the scattered coherent signal, both components could either add up destructively or constructively. At the specular reflection point, the incident angle equals the scattered angle, i.e., $\theta_i = \theta_s$. Furthermore, the azimuth angles of the incident and scattered waves have a difference of π . Using the geometries depicted in Fig. 8, the channel gain for the two-ray path is calculated by

$$a^{\text{co}}(t) = \left(\frac{\lambda}{4\pi} \right)^2 \left| \frac{\sqrt{g^{\text{LOS}}(t)}}{d_m(t)} + \frac{\sqrt{g^{\text{co}}(t)}\Gamma(t)e^{-j\Delta\varphi^{\text{co}}(t)}}{d'_{m1}(t) + d'_{m2}(t)} \right|^2. \quad (2.44)$$

Due to the directive antennas of the FS and the aircraft SATCOM antenna, the channel gains of the LOS and the specularly reflected path differ. Hence, g^{LOS} summarizes all gains and losses listed in (2.41), except for the free space path loss, and g^{co} comprises all gains and losses for the coherent reflected path ($\theta_i = \theta_s$). The free space path loss according to (2.42) is considered by the initial factor $(\lambda/4\pi)^2$ and the respective distances in the absolute of (2.44). The Fresnel reflection coefficient Γ of the Earth's surface at the specular reflection point is calculated depending on the considered polarization of the aircraft receiver and the FS station according to (2.26). The phase difference $\Delta\varphi^{\text{co}} = 2\pi(d'_{m1} + d'_{m2} - d_m)/\lambda$ is taken from the pertaining lengths of the coherent and the LOS paths.

Fig. 12 plots ζ attenuated by the channel gain derived in (2.44) for the single-entry reference scenario, for two FS antenna elevations. The results show that the specular reflection of FS RFI causes fading of the LOS component. However, the resulting fading depth cannot reduce the highest interference levels. Likewise, the constructive addition of the LOS and the coherent reflection does not increase the total FS RFI. Larger fades are observed at shorter distances, where fuselage attenuation and the low off-axis gain of the FS antenna reduce the FS RFI. The impact of the fading depth on the received signal is to be evaluated.

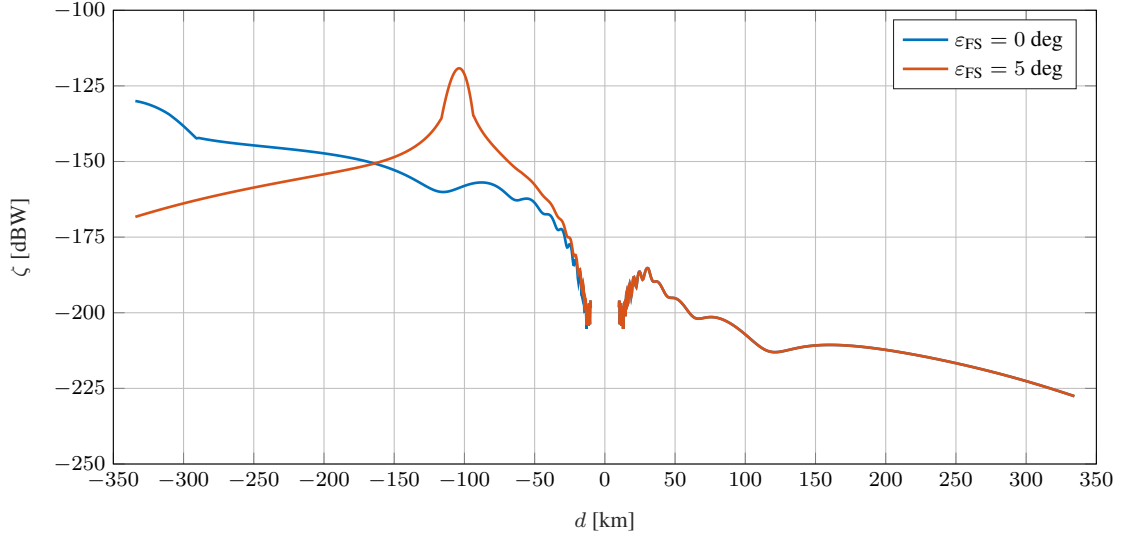


Figure 12: Fixed service radio frequency interference power ζ including the specular reflection component for two fixed service station antenna elevations, shown as a function of the distance d between the aircraft and the fixed service station.

2.3.3 Diffuse Multipath Components

Random diffuse scattered components can occur at any point in the FS and the aircraft's radio visibility area. Under the assumption that the channel is wide-sense stationary uncorrelated scattering (WSSUS) for very short periods, the randomly scattered components are considered Rayleigh distributed [35]. The channel gain for the scattered non-coherent component can be described by

$$a^{\text{nco}}(t) = \left(\frac{\lambda}{4\pi} \right)^2 \sum_{v=1}^V \left| \frac{\sqrt{g_v^{\text{nco}}(t)} \sqrt{a_v^{\mathcal{R}}} e^{-j\varphi_v^{\text{nco}}}}{d_{v1}^r(t) + d_{v2}^r(t)} \right|^2, \quad (2.45)$$

where the amplitudes of the reflected signals are formed by the Rayleigh parameter $a_v^{\mathcal{R}}$, describing a Rayleigh distributed random variable with variance σ_d , $a_v^{\mathcal{R}} \sim \mathcal{R}(\sigma_d)$. The phase is uniformly distributed $\varphi_v^{\text{nco}} = \mathcal{U}(0, 2\pi)$. The variance of the Rayleigh distribution depends on the surface roughness $r_s = (\sigma_h \sin \theta_i / \lambda)$, where σ_h is the root mean square of the surface height. For the assumed system model, information from [36] representing typical vegetation, i.e. $\sigma_h = 0.05$ m is used. The variance σ_d of the Rayleigh distribution is also depending on the surface roughness. To date, no data for representative land surfaces could be found in the literature.

In [37], a Rayleigh variance for the sea is provided. Since sea surfaces generally exhibit stronger diffuse scattering than typical land surfaces, the use of the Rayleigh variance derived for the sea represents a conservative assumption for land-surface scenarios, which is calculated by

$$\sigma_d \hat{=} \begin{cases} 3.68\sqrt{2}|\Gamma|r_s & 0 < r_s < 0.1 \\ \sqrt{2}|\Gamma|(0.454 - 0.858r_s) & 0.1 \leq r_s < 0.5 \\ 0.025\sqrt{2}|\Gamma| & r_s \geq 0.5 \end{cases} \quad (2.46)$$

Being dependent on the surface roughness r_s and the Fresnel reflection coefficient Γ , the variance for a sea surface would result in a range of $\sigma_d = \{1.85 \cdot 10^{-5}, 0.28\}$. This range is used to indicate the impact of the diffuse MPCs. In contrast to the investigations performed for the LOS and coherent component, the non-coherent MPCs are reflected from any point in the intersection of the radio horizon of the aircraft with the FS station. To reflect this in the reference single-entry interference scenario, random reflection points in the intersecting area are chosen to cope with differences in incident and scattering angles.

The number of diffuse MPCs is limited to $V = 6$, as additional components beyond this number contribute negligibly to the total received power due to increased path loss and low antenna gain at large reflection angles. Furthermore, statistical metrics of the non-coherent sum converge rapidly, making six components sufficient to capture the diffuse-scattering behavior while keeping the computational complexity low.

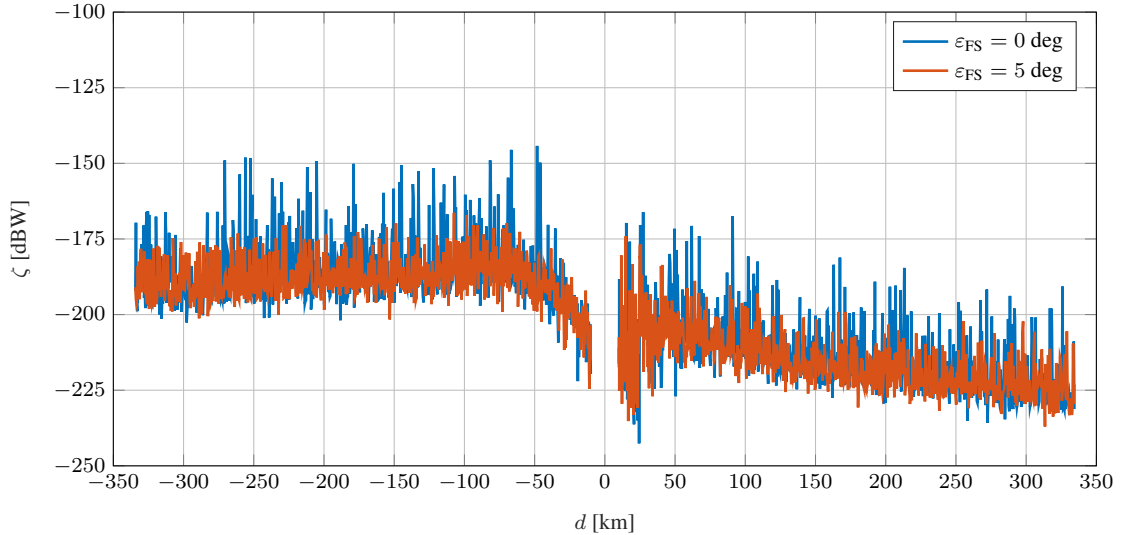


Figure 13: Fixed service radio frequency interference power ζ of the non-coherent components for two fixed service station antenna elevations, shown as a function of the distance d between the aircraft and the fixed service station.

Fig. 13 plots ζ attenuated by the channel gain derived in (2.45) for the single-entry reference scenario, for two FS antenna elevations. The diagram shows that lower elevations of the FS station would be subject to an increase of the MPC levels. This is due to the lower antenna gain discrimination of the FS antenna towards the ground. Compared to the LOS or coherent reflection the interference levels are lower. In Fig. 13, no pronounced maxima of the FS main lobe are observed in contrast to the other LOS and coherent interference profiles in Figs. 11 and 12. This is because a ground reflection in a plane-Earth model is assumed, in which the FS station antenna consistently exhibits high discrimination toward the Earth's surface. However, reflections from buildings or other structures within the FS station's main lobe could result in stronger diffuse components. In such cases, the LOS path would likely be shadowed.

2.3.4 Aggregation of all Components

Aggregating all single propagation elements in a composite interference leads to the plot in Figure 14, which is complemented by two more graphs adding the receive noise to the interference. Based on the information provided in the Report ITU-R S.2464-0 [38] the system noise temperature in the 17.7-19.7 GHz frequency range is $T_N = 189$ K. The received interference-plus-noise level is then calculated by $\zeta + p_N = \zeta + k_B T_N B_{AC}$, where $k_B = -228.6$ dB(J/K) is the Boltzman constant. The noise bandwidth $B_{AC} = 20$ MHz is chosen based on the typical GSO link budget provided in Table 2.

Fig. 14 shows that the impact of MPCs and fading of the dominant LOS component, especially for the interference level above the receive noise, is marginal. The critical FS RFI levels, caused by the main lobe of the FS stations, are not increased or decrease by

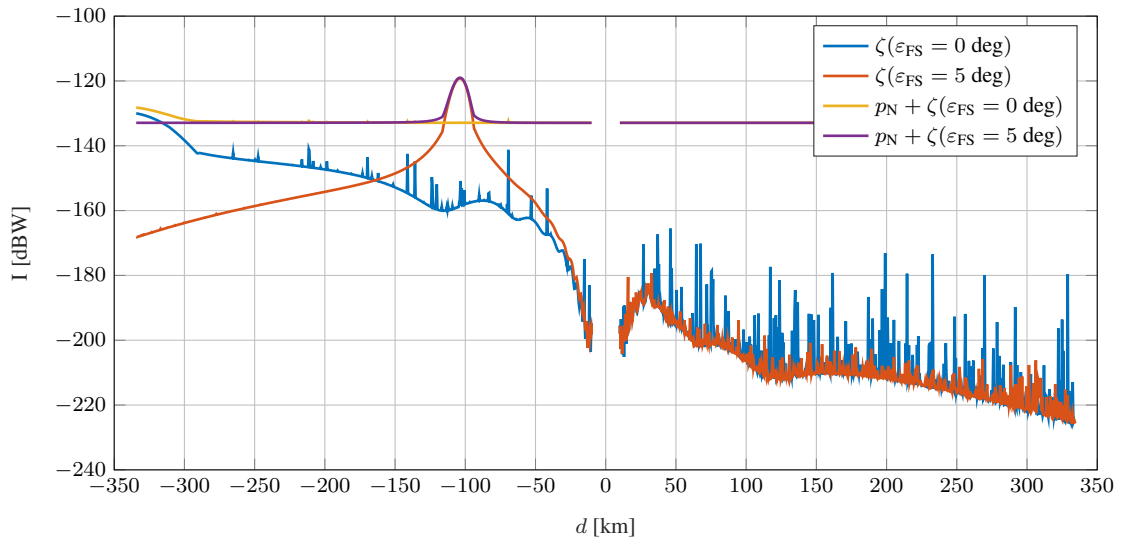


Figure 14: Aggregation of all fixed service radio frequency interference power components, line-of-sight, coherent, and non-coherent, for two fixed service station antenna elevations, shown as a function of the distance d and compared to the received interference-plus-noise power at the aircraft receiver.

diffuse multipath scatters. If the LOS FS RFI is low due to a smaller FS antenna diameter or large gain discrimination, MPCs are getting dominant but are then sufficiently below the noise floor (> 25 dB).

Hence, coherent and non-coherent components can be considered for accurate modeling of FS RFI. However, they do not significantly contribute to the IFE link's performance reduction. The LOS component remains the dominant element, which is shown in Fig. 14 to increase the noise floor by a significant amount (here > 10 dB). Therefore, the following section of this thesis focusses on the LOS component and its associated parameters. Section 2.4.4 discusses the possibility of frequency dispersion due to the Doppler effect on the reflected paths.

Key Takeaway

The LOS component dominates the FS RFI, driven primarily by the FS antenna gain and the geometric alignment. While specular reflections introduce fading and diffuse components contribute to low-power scattering, neither significantly impacts the overall interference profile compared to the LOS contribution.

2.4 Discussion and Selection of Relevant Channel Gain Parameters

In addition to simplifying the elements to be considered in the channel model, it is discussed whether all identified parameters in the LOS channel gain (2.41), respectively, impacting the channel gain, are relevant to be modeled and how they are modeled.

2.4.1 Flight Altitude

The flight altitude of the aircraft has a significant impact on the received interference power. It is intuitive that with increasing flight altitude, the slant path towards the FS station increases, and thus, the attenuation by the free space path loss increases. Moreover, higher altitudes would increase the path length through the atmosphere, which is affected by rain. This is depending on the geometry between the particular location of the FS station and the aircraft. The affected path length is determined by the rain height h_R defined in Rec. ITU-R P.839-4 [39] and is in maximum $h_R = 6.641$ km. Conversely, with increasing flight altitude, the radio horizon increases and more FS stations become visible, potentially interfering with the aircraft receiver. The received FS interference power ζ as a function of distance for a single-entry interference case is provided in Fig. 15. It shows four exemplarily chosen flight altitudes receiving interference signals from a single-FS station during a flight directly crossing the station.

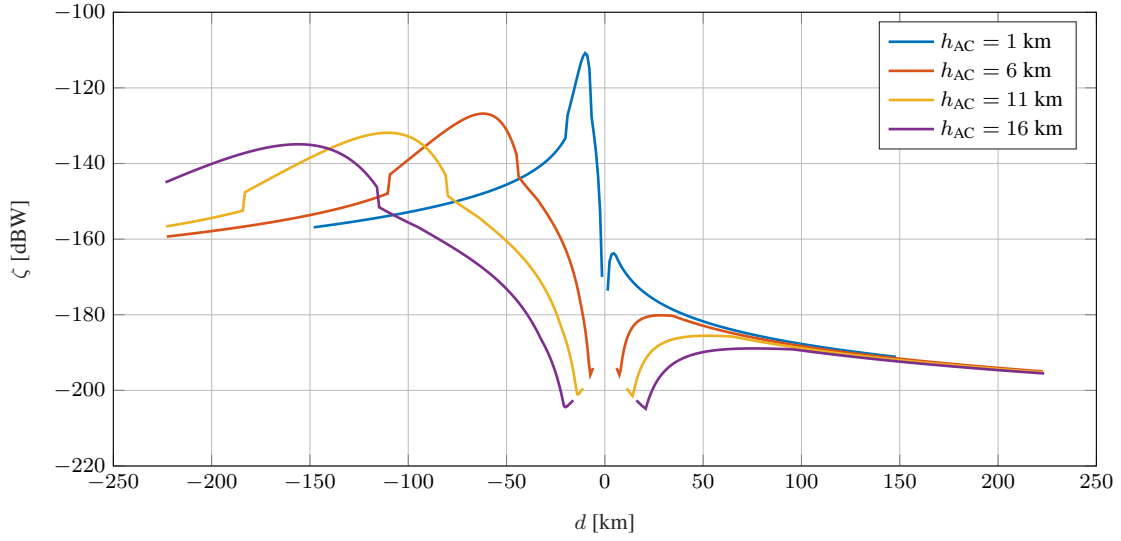


Figure 15: Fixed service radio frequency interference power ζ of the dominant line-of-sight component, shown for different flight altitudes h_{AC} , shown as a function of the distance d between the aircraft and the fixed service station.

The interference power due to the low free space path loss is high at low altitudes, but the time these high levels occur is limited, depending on the aircraft's speed above ground. The interference is short-term, i.e., high interference levels are caused for a relatively short period. In the worst-case scenario, such short-term events could lead to synchronization loss of the modem in the aircraft.

With increasing flight altitude, the interference power decreases. However, the number of samples/the amount of time, during which the A-ESIM receiver experiences interference, is longer than at lower altitudes. At those flight altitudes, the interference is of a long-term nature, causing interference events for a more extended period with a lower probability of causing severe interference events than at lower flight altitudes.

Despite evidence that lower flight altitudes can lead to higher interference events, high flight altitudes are modeled in this thesis, as the cruise phase at such altitudes represents the predominant portion of a commercial flight during which IFE services are provided. Flight altitudes may differ for applications outside IFE, such as unmanned aircraft systems (UASs) controlled via satellite(s). UASs operate over a wide range of altitudes, from very low to very high (cf. Res.155 (WRC-19)[40]). All steps performed for high flight altitudes in this thesis can be applied to other altitudes; however, a generalized model covering all altitudes has not yet been developed.

Flight phases identify the operational stages during an aircraft's flight and are defined differently. While there are multiple definitions and acronyms for flight phases, the most commonly used are given by the International Civil Aviation Organization (ICAO) [41].

Most of the time, and especially for long-haul flights, an aircraft provides IFE in the en-route phase at cruising altitude. That is also in line with the regulatory restrictions in Res. 169 (Rev. WRC-23) where Annex 3 Part II provides different pfd limits per flight altitude for the return uplink from the A-ESIM to the FSS space station. At higher flight altitudes $h_{AC} > 3$ km a higher transmit power for broadband applications is enforced. Thus, the aggregate FS RFI model for IFE is considered for the en-route phase of the aircraft at cruising altitude only.

2.4.2 Flight Path

A commercial aircraft in the en-route phase is heading toward its destination without any significant changes in direction. Reasons for changing the heading are mainly due to bad weather conditions or restrictions in the airspace due to safety reasons. An example for safety reasons is the military invasion by Russia, causing the risk of unintended targeting of civil aircraft by the military, misidentification, or confusion. The Ukrainian airspace is closed [42], and thus, aircraft fly around the territory of Russia and Ukraine. Another example is that an airline gets no rights for overflight by a country [43]. These are specific cases and are outside the regular operation of an aircraft. For the model, a great-circle flight path is assumed for A-ESIMs, represented by the orthodromic distance between the departure and destination points.

$$d_{\text{ortho}} = r_E \cos^{-1} (\sin \text{Lat}_a \sin \text{Lat}_e + \cos \text{Lat}_a \cos \text{Lat}_e \cos (\Delta L)) \quad (2.47)$$

where $\Delta L = \text{Lon}_a - \text{Lon}_e$ denotes the difference of longitude of the start and the end-points, and Lat_a and Lat_e the latitudes of the start and endpoints.

In case of a more random flight path that might occur during the approach, or, e.g., with UAS' operating in a surveillance mode, a repetitive pattern of the FS RFI might be observed, which could be worse in the case of larger FS station antennas and EIRP, respectively. These random-like flight paths would be subject to further studies and are discussed in section 6.2.

2.4.3 Atmospheric Impairments

Atmospheric impairments consist of several propagation effects that influence the signal strength on both the desired air-to-space and interfering air-to-ground links. From a performance perspective, impairments must be considered for both paths. The SATCOM link (space-to-Earth), which carries the desired signal, and the interfering air-to-ground link are affected differently depending on the aircraft's flight altitude.

When impairments occur on the interfering path, they are generally beneficial as they attenuate the FS RFI. Conversely, such impairments degrade performance on the desired

path by reducing the received power of the IFE link.

A statistical model for estimating atmospheric effects on radio links is provided in Rec. ITU-R P.618 [44]. It includes contributions from gaseous attenuation, rain, clouds, scintillation, and local phenomena such as sand and dust storms. The application to air-to-ground and air-to-space paths is provided in Rec. ITU-R P.2041 [45]. The total atmospheric attenuation in the logarithmic domain, A_T , is modeled as the sum of different contributions, as shown in (2.48).

$$A_T(p) = A_G(p) + \sqrt{(A_R(p) + A_C(p))^2 + A_S(p)^2} \quad (2.48)$$

$A_T(p)$ represents the attenuation not exceeded for a given probability p , comprising gaseous attenuation A_G and the root-sum-square of rain attenuation A_R , cloud attenuation A_C , and scintillation A_S .

Gaseous Attenuation: Gaseous attenuation, caused by the absorption due to oxygen and water vapor, can be estimated using Rec. ITU-R P.676 [46]. Unlike other impairments, it continuously affects the signal whenever the transmitter or receiver is located within the atmosphere. Depending on the slant path and atmospheric composition, attenuation levels typically range from 1 to 3 dB in the K- and Ka-bands. If local atmospheric data is unavailable, standard profiles from Rec. ITU-R P.835 [47] and a default surface water vapor density of 7.5 g/m³ [46] are recommended.

Rain Attenuation: Rain is the dominant source of attenuation in frequencies above 10 GHz. Its severity depends on the frequency, the slant path geometry, and the altitude of the terminal. Attenuation values exceeding 10 dB are common in the K- and Ka-bands. The statistical model of rain attenuation is also described in Rec. ITU-R P.618 [44], which accounts for slant path geometry and station altitudes. The slant path L_S for the SATCOM downlink denotes the distance from the transmitting or receiving station to the rain height at the prevailing elevation angle and is defined for the A-ESIM as

$$L_S = \begin{cases} \frac{2(h_R - h_{AC})}{\sqrt{\sin(\varepsilon_{AC})^2 + \frac{2(h_R - h_{AC})}{r_E}} + \sin(\varepsilon_{AC})} & \text{for } \varepsilon_{AC} \leq 5^\circ \\ \frac{2(h_R - h_{AC})}{\sin(\varepsilon_{AC})} & \text{for } \varepsilon_{AC} > 5^\circ. \end{cases} \quad (2.49)$$

It holds that the rain-affected length of the air-to-ground path d is always greater than the downlink slant path L_S towards the aircraft flying below the maximum rain height:

$$L_S < d \quad \forall h_{AC} < \max(h_R) \text{ km.} \quad (2.50)$$

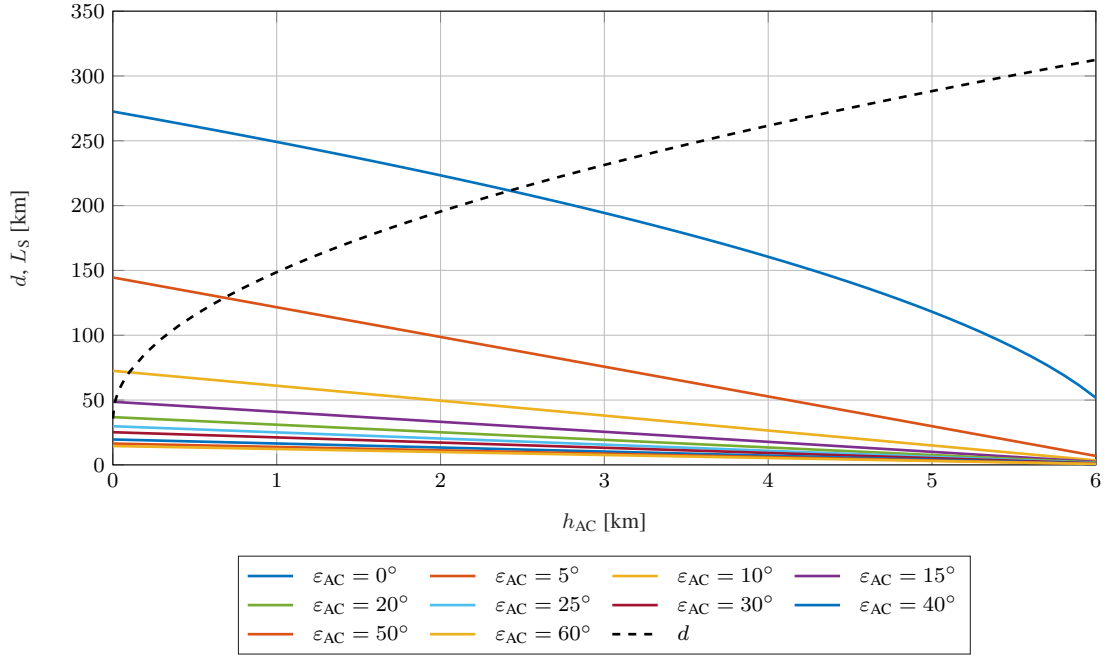


Figure 16: Comparison of the slant ranges affected by rain for different aircraft antenna elevations, showing the air-to-space path from the aircraft to the rain height and the air-to-ground path from the fixed service station to the aircraft, at the maximum rain height of $h_R = 6.641$ km, as a function of flight altitude.

The difference in path lengths affected by rain in the air-to-ground path and in the space-to-Earth path according to (2.49) and (2.5) are plotted in Fig. 16.

Cloud Attenuation: Cloud attenuation becomes relevant above 10 GHz and is modeled using Rec. ITU-R P.840 [48]. It applies only when the aircraft flies above the rain height, where clouds dominate over rain as the primary impairment. Based on standard cloud height definitions in Rec. ITU-R P.839 [39], this type of attenuation is expected primarily in en-route flight segments and mainly affects the interfering air-to-ground link.

Scintillation: Scintillation is caused by ionospheric irregularities and results in rapid amplitude variations of the received signal due to refractive focusing and defocusing. Above 10 GHz, its peak-to-peak effect can reach up to 4 dB [44]. Scintillation is typically more pronounced in conjunction with rain.

In severe rain conditions, attenuation on the interfering path can reach up to 30 dB in the K- and Ka-bands, depending on aircraft and FS station locations. However, such extreme effects are region-specific and cannot be generalized. Furthermore, the probability of simultaneous rain and cloud attenuation on both links depends on the size and shape of the rain cells and the angular separation between the two paths as seen from the aircraft. When both paths are closely aligned in azimuth, their rain attenuation can be spatially

correlated [49, 50]. In uncorrelated conditions, only one of the paths may experience rain attenuation, and one can either consider the wanted link or the interfering link under rain, which is, in both cases, unrealistic and, respectively, overly conservative.

In this thesis, the interference assessments assume clear-sky conditions, leading to a simplified model with $A_T(p) = A_G(p)$ and no assumed correlation between the two paths.

2.4.4 Doppler Effect

In wireless communication channels, the Doppler effect causes a constant frequency shift in the received signal and is crucial when considering multipath propagation. When radio signals propagate along different paths to the receiver, which receives them at different angles and delays, the relative motion between the transmitter and receiver creates unique Doppler shifts for each path. The combination of these frequency-shifted components results in Doppler spread, leading to fast fading, characterized by rapid signal amplitude and phase fluctuations over time. These fluctuations can cause frequency-selective fading and inter-symbol interference (ISI), especially in wideband systems.

In the context of interference from terrestrial FS stations to an aircraft operating in the air-to-ground path, ISI on the unwanted signals $\tilde{y}(t)$ is negligible. However, the Doppler effect can lead to significant variations in the observed frequency of the interfering carrier due to the relative motion between the aircraft and the FS station. The Doppler-induced frequency shift is determined by the aircraft's velocity relative to the FS station and impacts the interference dynamics. It is given by:

$$f_D = \frac{v_{AC} \cos(\gamma)}{\lambda} = \frac{v_{AC} \cos(\gamma) f_c}{c_0} \quad (2.51)$$

where v_{AC} is the relative velocity between the aircraft and the FS station, γ is the angle between the velocity vector of the aircraft and the LOS to the FS station. Substituting $f_c = 18$ GHz, the Doppler shift is

$$f_D = \frac{v_{AC} \cos(\gamma) \cdot 18 \text{ GHz}}{c_0} = 60 \cdot v_{AC} \cos(\gamma) \text{ Hz/m/s.} \quad (2.52)$$

Typical aircraft speeds in the en-route flight phase are in the range of 200-300 m/s [18]. The resulting the Doppler shift could range from:

$$f_D = 60 \cdot 200 \cdot \cos(\gamma) \text{ Hz} \quad \text{to} \quad f_D = 60 \cdot 300 \cdot \cos(\gamma) \text{ Hz}, \quad (2.53)$$

or approximately $f_D \approx 12...18$ kHz when $\gamma = 0^\circ$, i.e. when the aircraft is moving directly toward or away from the FS station. Hence, the Doppler spread on any FS RFI signal is $B_D = f_{D, \max} - f_{D, \min} = 12...18$ kHz. Although $B_D \ll B_{AC}$ the Doppler effect may

still introduce frequency dispersion due to time-varying frequency shifts across the signal bandwidth.

Frequency-selective fading becomes significant when the channel's coherence bandwidth is smaller than the signal bandwidth. Frequency-selective fading distorts the signal spectrum, as the frequency components are no longer uniformly displaced. When considering the impact of frequency-selective fading on the unwanted signal $\tilde{y}(t)$, the potential ISI is only considered when the fading in the interfering signals affects the wanted signals, too. Figs. 13 and 14 already demonstrated that the diffuse MPCs are not dominating the receiver signal.

Therefore, the channel is modeled considering only the Doppler frequency shift, while frequency-selective effects are excluded. This might be different for narrow band emissions $B_{AC} \ll 1$ MHz .

2.4.5 A-ESIM Antenna Reference Pattern

IFE-SATCOM antennas are installed and operated on various aircraft and architectures. They are designed as rotational symmetric reflector antennas installed in the nose of an aircraft, flat panel antennas, or even beamforming antennas mounted on the top of the fuselage of an aircraft, as depicted in Fig. 17.

From the ITU-R perspective and reported in [38], A-ESIMs are of two types depending on how the antenna is mounted on an aircraft.

- (1) A tail mount antenna is a two-axis stabilized earth station employing a 30 cm or larger aperture diameter antenna. The antenna is typically a circular aperture with a symmetrical center-fed design.
- (2) The fuselage-mounted A-ESIM is a two-axis stabilized earth station employing an asymmetrical rectangular array antenna with typical dimensions of around 65 cm by 19.5 cm.

Larger aperture antennas are also used, depending on the aircraft size. This type of antenna is mounted on the top of the aircraft fuselage. Both types consist of the stabilized antenna and relevant electronics enclosed in a protective radome designed for operation aboard aircraft.

A-ESIM antennas shall comply with Rec. ITU-R S.580-6 [21]. This Recommendation defines a rotational symmetric reference pattern for typical FSS antennas. The flat panel or beam-forming antennas might deviate from that reference envelope pattern, as those do not exhibit a rotationally symmetric beam pattern. However, these are still obliged to stay within this antenna gain envelope.

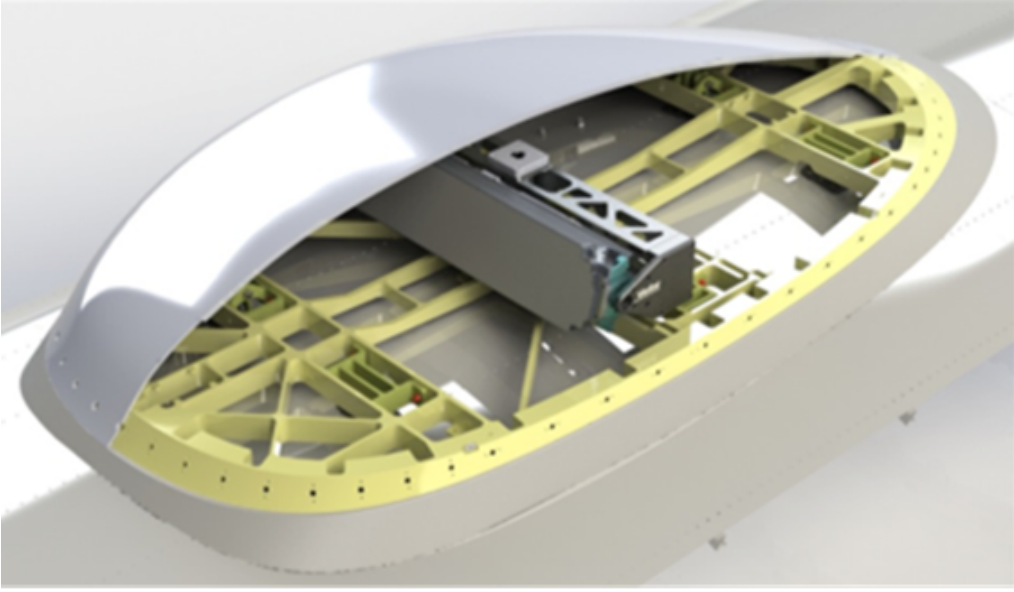


Figure 17: Typical fuselage-mounted satellite communication antenna assembly on an aircraft [38].

The impact of FS RFI using a low-profile antenna compared to a dish-type antenna complying with the antenna envelope of Rec. ITU-R S.580-6 does not have significant relevance for the interference levels but rather for the performance of the SATCOM link. Due to the relatively small on-axis gain of a low-profile antenna compared to the same off-axis gain of the reference antenna pattern envelope, the SATCOM link would have less margin available to compensate for the FS RFI (see IFE LB in Table 2).

The aircraft antenna diameters, respectively, and the equivalent antenna gains g_{AC} for A-ESIM antennas are reported to start from a $D_{AC} = 0.3$ m equivalent up to $D_{AC} = 1.2$ m. Fig. 18 shows the antenna pattern based on the Rec. ITU-R S.580-6 for the A-ESIM antenna diameter $D_{AC} = \{0.3 \text{ m}, 0.6 \text{ m}, 0.9 \text{ m}, 1.2 \text{ m}\}$ and for off-axis angles $\varphi_m = \{10 \dots 180\}$ degrees. The range on the x-axis corresponds to the considered system model in terms of the spatial angle between the antenna pointing vector of the aircraft satellite antenna and the location of the m th FS station.

The limit of 15, respectively 10 degrees, is chosen for the diagram, as this is the worst-case antenna elevation of the A-ESIM towards the respective GSO satellite, providing reasonable IFE link performance in the considered frequency range. Fig. 18 shows that when using the antenna pattern envelope of Rec. ITU-R S.580-6, for $D_{AC} \geq 0.9$ m, whose formulas are provided in Appendix A, the off-axis gain for $\phi_m > 10$ degrees is equal for all diameters. Accordingly, the off-axis gain $G_{AC}(\phi_m)$ has fixed values that depend only on ϕ_m . Moreover, Fig. 18 shows that the difference between the off-axis antenna gains for antennas having a $D_{AC}/\lambda < 50$ is constant. The relation in the far sidelobes can be used to scale the interference model to different antenna sizes and center frequencies.

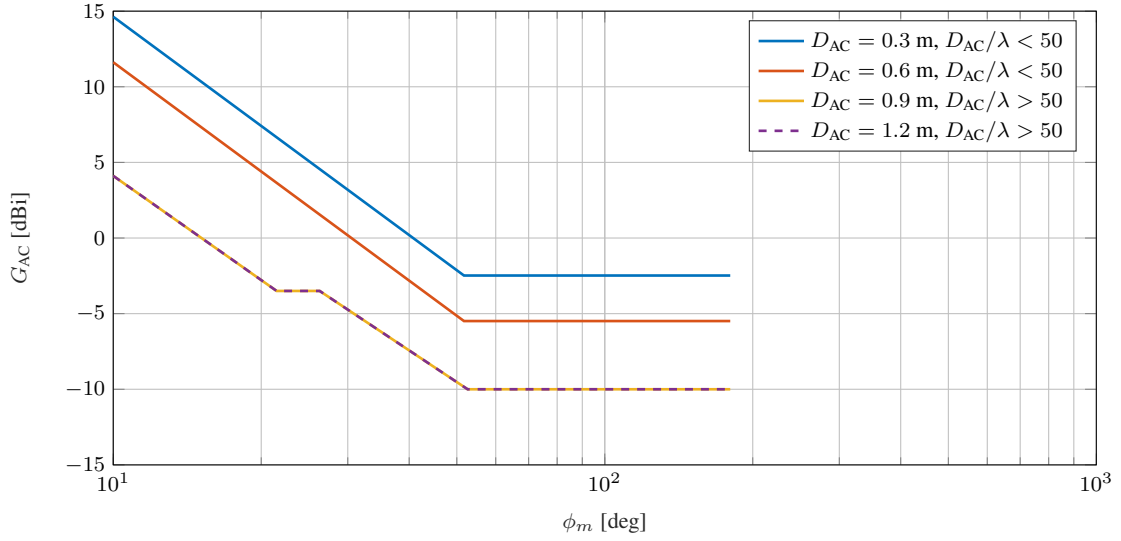


Figure 18: Rotationally symmetric antenna reference patterns according to Recommendation ITU-R S.580-6 from the International Telecommunication Union Antenna Pattern Library [21], shown for different satellite communication antenna diameters D_{AC} at a center frequency of $f_c = 17.7$ GHz and an antenna efficiency of 65%.

2.4.6 Fixed Service Station Antenna Reference Pattern

The FS stations' antenna radiation pattern is given in Rec. ITU-R F.1245-3 [51]. It provides the envelope for sharing studies with multiple interference sources. The reference patterns for several antenna gains reported for stations using FS are depicted in Fig. 19. Typical technical and operational characteristics of FS use in several countries are provided in Rec. ITU-R F.758-7 [31]. It can be observed that these stations exhibit a high front-to-back-ratio (FBR). The difference between the back lobe ($\theta_m > 48$ degrees) and the main lobe ($\theta_m = 0$ degrees) is at least 43 dB and a maximum of 63 dB. Due to the large FBR, the high variations in the RFI signal levels are expected as the variations of that antenna gain are higher than the variations in gain or attenuation from the aircraft antenna gain, the fuselage attenuation, or the free space path loss during a flight over a single FS antenna.

2.4.7 Fuselage Attenuation

The attenuation caused by the aircraft fuselage obstructing signals is often discussed in the literature when aeronautical communication links are studied. It is well known that the fuselage obstructs and attenuates signals depending on several variables. However, its specific impact on interference from FS RFI into aeronautical communication links, particularly those involving A-ESIMs, remains a complex topic that is constantly evolving within the concerned groups of the ITU-R.

Multiple factors influence the level and impact of an aircraft fuselage obstruction, such as, e.g., the aircraft design. Each aircraft exhibits unique attenuation characteristics due

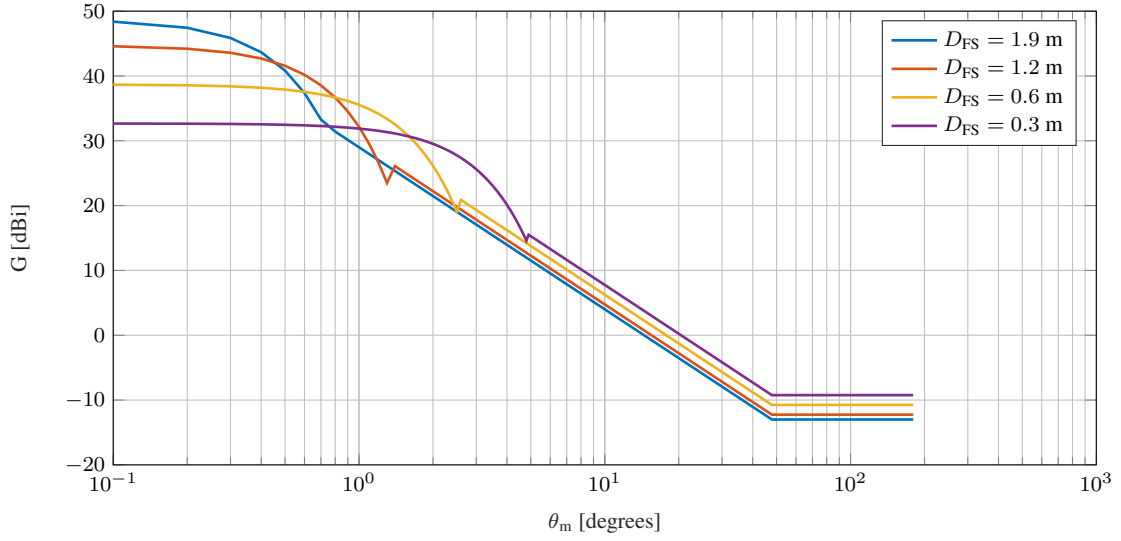


Figure 19: Rotational symmetric antenna reference pattern according to Recommendation ITU-R S.580-6 of the International Telecommunication Union Antenna Pattern Library [52] for different fixed service antenna diameters D_{AC} at $f_c = 17.7$ GHz and an antenna efficiency of 65%.

to its dimensions, fuselage shape, and antenna mount location variations. Furthermore, the materials used in aircraft construction affect signal propagation. Finally, the fuselage blockage is most significant for antennas mounted on top of the aircraft, as the fuselage can shield signals arriving from below or at sharp angles. Antennas placed in the nose of an aircraft have less blockage.

Fuselage attenuation values have been measured and documented for the frequency range relevant to A-ESIM operations. For instance, Boeing 737 measurements in [53, 54] provide empirical data, while simulated attenuation characteristics are available in [55] for alternative aircraft configurations. Fig. 20 plots the fuselage attenuation as a function of the angle below the horizon, as provided in [53, 54]. However, those values for fuselage attenuation have been mainly addressed in the Ku-band frequency range of 14-14.5 GHz, where the initial studies for ESIMs have been initiated. ITU-R study groups continue to analyze fuselage effects within the framework of Res. 169 (Rev. WRC-23) in the K- and Ka-band frequency ranges, demonstrating that the ratified fuselage in [53] is applicable in the 17.7-19.7 GHz frequency range, as long as no other measured values are made available.

The primary cause of fuselage attenuation in A-ESIM links is the aircraft's body's physical blockage of LOS signals. However, some radio energy may creep around the fuselage surface even with this obstruction, producing secondary creeping waves. These waves allow signals to partially propagate around the aircraft, though at significantly reduced power. Fig. 21 illustrates an example of fuselage surface currents resulting from creeping waves. Such attenuation effects are pronounced at angles approaching 90 degrees from

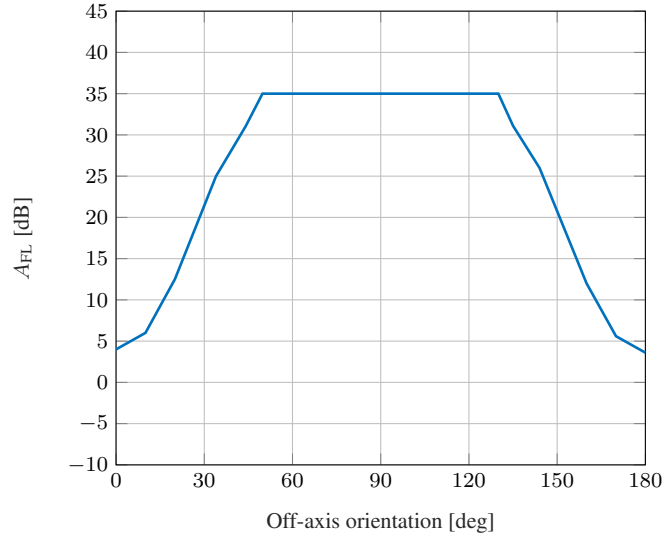


Figure 20: Measured fuselage attenuation due to the aircraft body on the roll-plane (i.e. for azimuth = 90°) with an antenna mounted on top of a full cylinder with radius of curvature approximately equal to that of a Boeing 737 fuselage[53].

the antenna's boresight, where fuselage obstruction is maximal. This analysis was conducted in [56], where the attenuation caused by fuselage blockage in the K- and Ka-band is assessed for an antenna mounted on the aircraft's fuselage.

To determine whether fuselage attenuation impacts the received interference power ζ and to what extent, the interference-to-noise ratio (INR) at the aircraft receiver was calculated across varying distances d between the aircraft and the FS station, factoring fuselage attenuation. The INR represents the ratio of received interference power from the FS station to the aircraft receiver's thermal noise power. It is defined by:

$$\text{INR} = \frac{\zeta[d]}{k_B T_N B_{AC}}. \quad (2.54)$$

$T_N = 189$ K is the typical receive noise temperature of the aircraft receiver, and $B_{AC} = 20$ MHz is a typical receive noise bandwidth for IFE, as shown in the IFE LB Table 2. The calculation first includes the fuselage attenuation of [56] and afterward excludes fuselage attenuation. The results in Fig. 22 demonstrate that the highest INR values vary with the distance d and depend on the FS antenna elevation ε_{FS} .

Furthermore, in cases where the FS RFI is above noise ($\text{INR} > 0$ dB) and, therefore, is severely impacting the performance of the SATCOM link, the attenuation of the fuselage attenuation is marginal. The fuselage significantly impacts the INR when the distance between the aircraft and the FS station is minimized, respectively, when the aircraft is directly above the FS station ($d = h_{AC}$). In that geometric case and for the selected FS elevations, the spatial angle between the FS station pointing vector and the aircraft

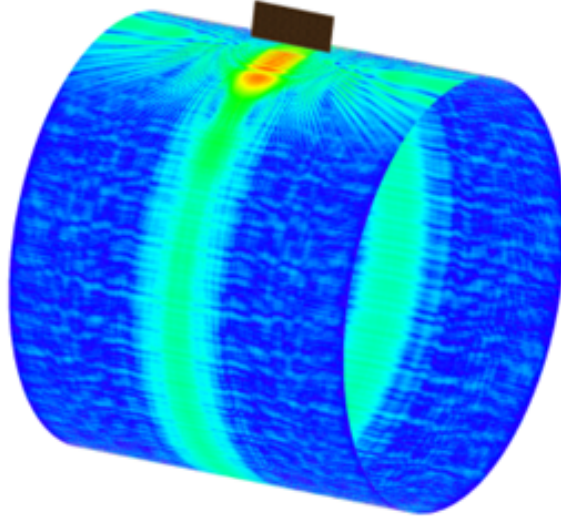


Figure 21: Example simulation results of fuselage surface currents, or “creeping waves,” from an antenna array mounted on top of the fuselage [56].

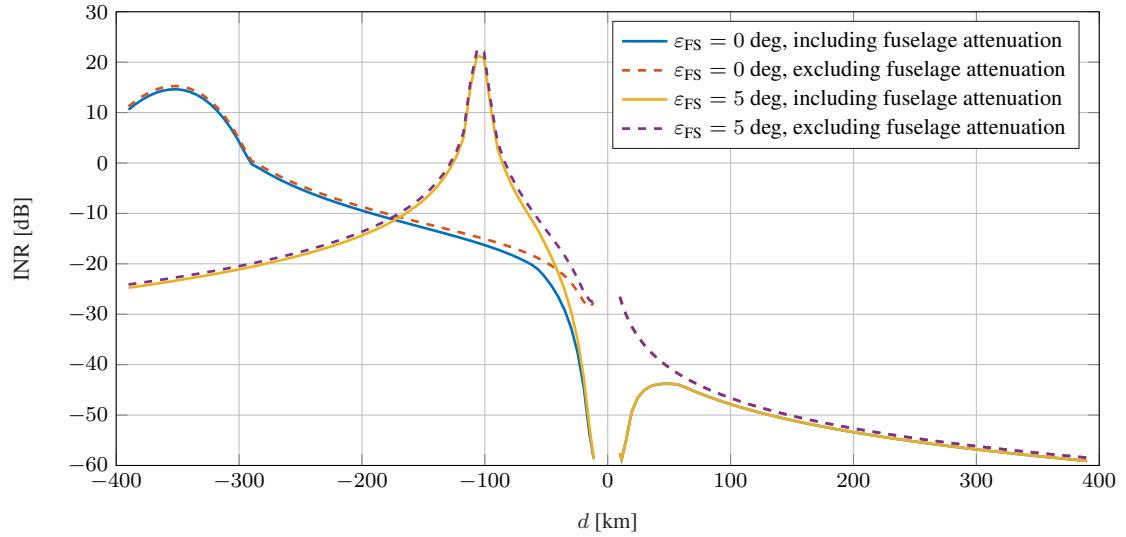


Figure 22: Interference-to-noise ratio at the aircraft receiver for a flight over a single fixed service station, comparing cases with and without fuselage attenuation, shown as a function of the distance d between the aircraft and the fixed service station.

is $\theta \leq 85$ degrees. According to [51], the FS gain at these angles is already in the FS antenna's back lobe. Even without considering fuselage attenuation, the caused FS RFI is already 27 dB below the noise floor. The higher RFI levels would be reduced by the fuselage if $\varepsilon_{\text{FS}} > 15$ degrees, which is probable but limited to a small number of FS stations with lower power as well as to limited regions with hilly terrain (e.g., Switzerland). Additionally, due to its dependency on the used aircraft, no generic model for fuselage can be applied.

Consequently, the effects of fuselage attenuation are omitted in the analysis to be independent from the considered aircraft and provide more conservative results applicable for a wider range of cases.

2.4.8 Polarization Loss

When a circularly polarized antenna receives linearly polarized FS RFI, the effective power of the interference is reduced due to the inherent polarization mismatch. A circularly polarized wave consists of two orthogonal components (horizontal and vertical), each with an equal magnitude but a 90-degree phase shift. On the other hand, a linearly polarized wave has a constant orientation. The polarization mismatch between a circularly polarized wave and a linearly polarized wave is derived from the projection of the linearly polarized electric field onto one of the orthogonal components of the circularly polarized wave, depending on the axial ratio of the polarizer in the receiver (e.g., an orthomode transducer or septum polarizer). To better understand the impact, the received power of the interference p_{rx} at the circularly polarized horn is calculated as:

$$p_{\text{rx}} = p^{\text{I}} \cdot \left(\frac{1}{\sqrt{2}} \right)^2 = p^{\text{I}} \cdot \frac{1}{2}. \quad (2.55)$$

This relationship shows that the interference power at the receiver is halved, resulting in a noticeable reduction.

Although referencing the polarization discrimination between two GSO satellites in the FSS, Rec. ITU-R S.736 [57] provides guidance in the determination of discrimination. In the case of an interfering wave in linear polarization (the linear polarization vector can be derived from two circular polarization vectors, right- and left-hand rotation), the discrimination obtained at the receive wanted antenna operating in circular polarization can be expressed in the following way:

$$Y_{\text{p}} = -10 \log_{10} \frac{1}{2} (1 + 10^{-D_{\text{p}}(\varphi)/10}) \quad (2.56)$$

where $D_{\text{p}}(\varphi)$ is the polarization decoupling of the receive antenna. In ITU-RR Vol. II Appendix 8 the numerical isolation between different polarizations is given. In Table 4,

Table 4: Polarization isolation used in International Telecommunication Union interference calculations

Polarization 1	Polarization 2	Factor polarization isolation (numerical ratio) Y_p
LHC	L	1.4
RHC	L	1.4

the left-hand circular (anti-clockwise) polarization is denoted by left hand circular (LHC), and right hand circular (RHC) denotes the opposite polarization. Linear polarization (vertical or horizontal) is denoted by linear (L). The polarization isolation $Y_p = 1.4$ to be considered is less than a factor of two, covering the potential variations in the off-axis domain, which could be even at some places close to zero. Furthermore, administrations are encouraged to deploy their national FS systems according to a specified harmonized channel arrangement of FS, always using linear polarizations (horizontal (H) and vertical (V)) according to European Radiocommunications Committee (ERC) Rec. 12-03 [58] and Rec. ITU-R F.595 [59], which is depicted in Fig. 23. Due to the extensive use of FS in that band and the missing information on the polarization of FS used in the MIFR, the guidance from Rec. ITU-R F.2086 [60] is used. Section 3.5.4 of that Recommendation states that traditional point-to-point systems typically alternate between links with horizontal and vertical polarization, and would have a roughly even split between the two polarizations. Systems using co-channel dual-polarization will use horizontal and vertical on every link, thus not considering that polarization loss is a conservative approach for FS RFI.

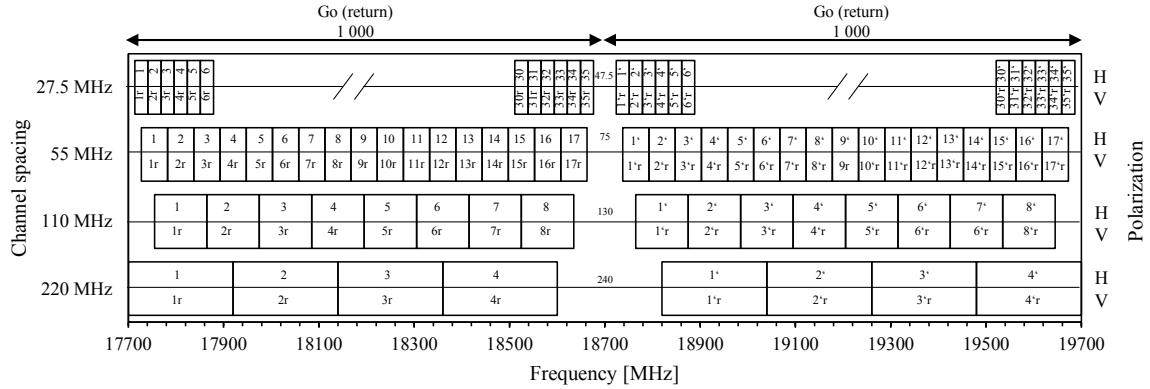


Figure 23: International harmonized channel arrangement of fixed service in the frequency range 17.7-19.7 GHz separating the spectrum in two bins for forward and return and using linear polarizations for frequency reuse according to [58, 59]

2.4.9 Receiver Bandwidth

The receiver bandwidth directly influences the received FS RFI power level. As the bandwidth increases, more FS stations may fall within the receiver's passband, increasing the potential for spectral overlap. In this context, the out-of-band (OOB) suppression characteristics of both the aircraft receiver and the FS transmitter must be considered. Let $a_B^{\text{FSS}}(f)$ denote the linear OOB attenuation of the FSS receiver, such as the A-ESIM, and $a_B^{\text{FS}}(f)$ the corresponding attenuation of the FS transmitter. The propagation channel between the FS station and the aircraft must also be considered. $\tilde{H}(t, f)$ denotes its time-varying frequency response. As discussed in Section 2.4.4, the LOS channel is assumed to be frequency-flat over the receiver bandwidth, provided the observation interval is sufficiently short. Under this assumption, the frequency response can be approximated by a constant attenuation factor, $\tilde{H}(f) = \alpha$. Accordingly, the received interference power is computed as follows:

$$p_{\text{Rx}} = \alpha \cdot \int_0^\infty \frac{\text{psd}^{\text{I}}(f)}{a_B^{\text{FS}}(f)a_B^{\text{FSS}}(f)} df, \quad (2.57)$$

where $\text{psd}^{\text{I}}(f)$ is the power spectral-density (psd) of the FS transmitter. Considering a finite OOB response, and the interference is evaluated within the receiver's occupied bandwidth B_o around the center frequency f_c , the total effective attenuation can be approximated by:

$$a_B^{\text{tot}}(f) = a_B^{\text{FSS}}(f) \cdot a_B^{\text{FS}}(f). \quad (2.58)$$

In absence of available filter characteristics of the FS transmitter and the aircraft receiver, Rec. ITU-R S.1541-7 [61], provides generic spectrum masks for the FS and FSS. The FSS mask is defined as

$$a_B^{\text{FSS}} = 40 \log_{10} \left(\frac{F}{50} + 1 \right) \text{ dBsd} \quad (2.59)$$

where $F = 100 \cdot f/B_n$ is the frequency offset from the edge of the total assigned band, expressed as a percentage of necessary bandwidth B_n . The unit dBsd are the decibels relative to the maximum value of psd within the necessary bandwidth. The maximum value of psd of a random signal is found by determining the mean power in the reference bandwidth B_{ref} when that reference bandwidth is positioned in frequency such that the result is maximized.

The FS mask is defined in [61] as discrete values per frequency as shown in Table 5. Those OOB emissions, despite being very conservative, are considered in the model, to cope for the correct implementation of partial overlapping carriers of the FS.

In Fig. 24, a simulation of the interference power ζ as a function of time versus frequency of the LOS component, including the spectrum masks, is performed, showing the potential frequency overlap of multiple interfering FS stations in the frequency range 17.8-

Table 5: Required suppression of out-of-band emissions for digital fixed service systems operating above 30 MHz, as specified in Recommendation ITU-R SM.1541-7 [61] distinguishing between frequency division multiple access (FDMA) systems and general systems. The attenuation is given in decibels relative to the maximum value of psd within the necessary bandwidth, and the frequency offset is expressed as a percentage of the channel separation (CS).

All systems (FDMA excluded)		FDMA systems only	
Frequency offset (CS %)	Attenuation (dBsd)	Frequency offset (CS %)	Attenuation (dBsd)
0	0	0	0
55	0	50	0
120	25	65	25
180	40	150	25
250	40	150	40
		250	40

18.2 GHz. Depending on the receiver bandwidth, respectively, the matched filter only parts of the interference power affect the wanted signals. Fig. 25 quantifies the number of visible FS stations M at a flight altitude of $h_{AC} = 10$ km as a function of the receiver bandwidth B_{AC} . This assessment is based on recorded FS links in the MIFR. The number of visible FS stations with overlapping frequencies increases with bandwidth. However, the downlink budget of the IFE link in Table 2 provides guidance for selecting a representative receiver bandwidth, as already used in (2.54).

A low noise block converter (LNB) downconverter may have a larger noise bandwidth, often splitting the entire 17.7-21.2 GHz range into subbands to enable sampling in the intermediate frequency range. In a Nyquist system, however, the matched filter bandwidth is dictated by the symbol rate and the pulse-shaping filter, which suppresses interference contributions such as FS RFI. The choice of $B_{AC} = 20$ MHz, based on the IFE LB, reflects the developed interference model and represents typical state-of-the-art technology used in GSO HTS networks and receiver designs.

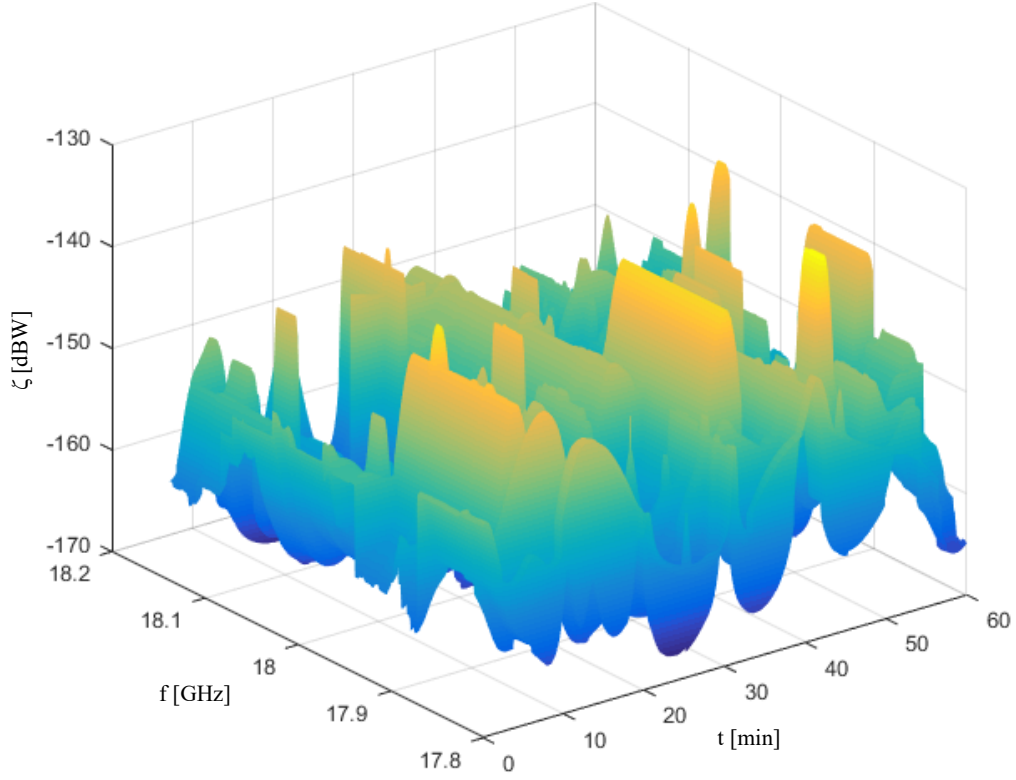


Figure 24: Simulation of the line-of-sight interference power ζ in the 17.8-18.2 GHz range, shown as a function of time and frequency. Different power levels and bandwidths of fixed service interference are illustrated, depending on the receiver bandwidth B_{AC} , which varies over time and frequency.

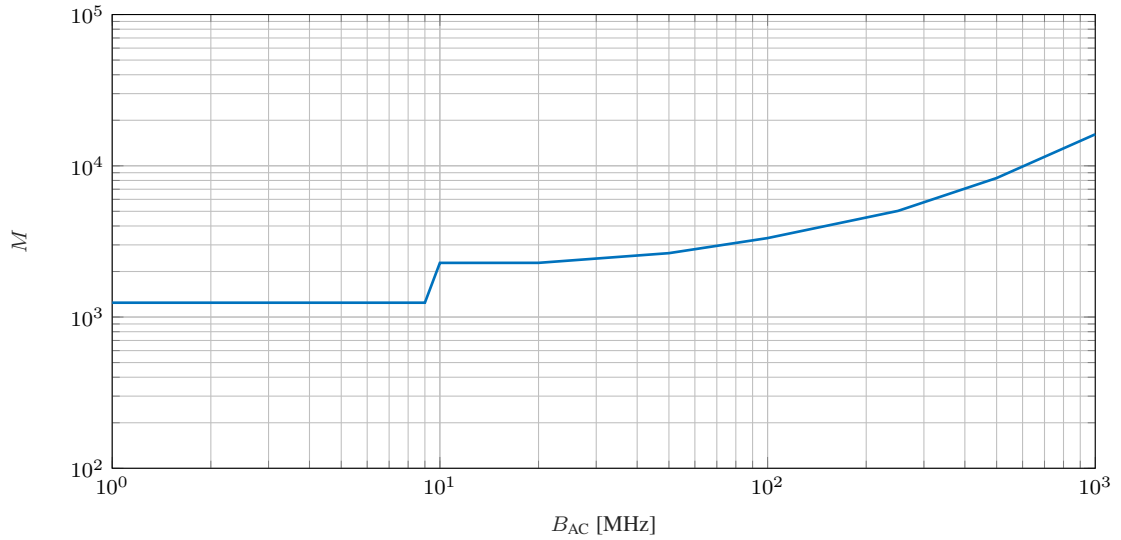


Figure 25: Number of visible fixed service stations M at a flight altitude of $h_{AC} = 10$ km, shown as a function of the receiver bandwidth B_{AC} at a center frequency $f_c = 18.2$ GHz.

2.4.10 Clutter and Diffraction

In air-to-ground paths, the propagation of radio waves is influenced by various environmental factors such as clutter and diffraction. Clutter refers to obstacles in the propagation path (e.g., buildings, trees), while diffraction accounts for the bending of radio waves around obstacles. Both effects are significant in indirect paths and environments where the signal encounters obstructions between the aircraft and the ground station.

These obstacles mainly occur in urban and suburban environments and significantly affect the propagation of radio waves, particularly at lower altitudes. The clutter loss due to obstacles in the air-to-ground path can be modeled using ITU-R Recs. and Reports (Reps.). Rec. ITU-R P.2108 [62] and Rep. ITU-R P.2402 [63] provide methods for calculating the additional attenuation due to clutter in various environments. As previously demonstrated in Fig. 3, the path from the FS antenna towards the airborne SATCOM receiver is mainly free of obstacles. By selecting a plane-Earth model and not considering MPCs, clutter has no significant impact on the receiver interference power, so that it can be omitted for the detailed modeling in the selected interference scenario.

2.4.11 Summary of Parameter Discussion

This section provides a consolidated overview of the system parameters analyzed in previous sections and their influence on the LOS channel gain between interfering terrestrial FS stations and the aeronautical satellite communication receiver. Tables 6 and 7 list these parameters categorized by system component, summarize their dependencies and physical impact, and assign a qualitative relevance based on their expected influence on the interference scenario. These tables support the decisions made regarding effects in subsequent modeling and justify which effects are included or excluded in the final simulation framework. Parameters marked with "high relevance" vary in the analysis or are retained as fixed design assumptions. In contrast, "low" and "medium relevance" parameters are considered for completeness but may have limited impact under the assumed scenario conditions.

Key Takeaway

Not all parameters in the LOS path equally affect interference from FS stations into the aeronautical SATCOM receiver; some can be neglected. The dominant contributions originate mainly from the FS antenna gain, the flight altitude, and the receiver bandwidth. The bandwidth is typically maximized to increase throughput, while the chosen flight route determines the flight altitude.

Table 6: Summary of system parameters influencing the channel gain between interfering terrestrial fixed service stations and aeronautical satellite communication receivers - Part I

System element	Parameter	Dependencies / Impact	Relevance	Section
Aircraft	Flight altitude	Influences the location, shape, and scale of the FS RFI probability density functions by the number of visible FS stations. En-route scenario at a flight altitude $h_{AC} = 10$ km selected, covering the most cruising altitudes in the en-route flight phase, where IFE is provided.	High	2.4.1
	Flight velocity	Causes a Doppler shift on FS RFI signals. f_D is significantly low at the K- and Ka-band frequencies and bandwidths considered. This has an impact on the level crossing rate and average duration of fades, which is normalized to f_D . While Doppler spread may theoretically impact ISI, its effect on the interfering FS signal path is negligible due to the dominance of LOS and the small Doppler-to-bandwidth ratio.	Low	2.4.4.
	Flight path	For commercial aircraft the flight path is relatively constant (great circle flight path). In the case of random paths, diverse interference events could occur.	Medium	2.4.2
	Fuselage attenuation	FS RFI signals are highly attenuated when the distance between the aircraft and the FS station is minimized and RFI level are already 28 dB below noise. Highest FS RFI levels are not attenuated by fuselage.	Low	2.4.7
	Antenna type /size	Determines off-axis antenna performance, attenuating FS RFI more with increasing antenna diameter. Flat panel antennas have worse performance than reflector antennas. The ITU-R antenna reference pattern is used per ITU-R regulation. Distinguishing between two D_{AC}/λ values, allowing the transformation of results into an arbitrary chosen diameter.	Low	2.4.5
	Antenna elevation	Provides higher antenna off-axis discrimination towards FS stations for higher elevation angles. Mainly impacts the operation at low aircraft latitudes with GSO networks.	Medium	3.2.2
	Receiver bandwidth	Higher levels of interference power due to a larger number of FS station having frequency overlap.	High	2.4.9
Fixed service	FS station density	Probability of frequency overlap increases with higher density. Differs on a country-by-country basis. FS stations are correlated with infrastructure such as cities or highways	High	3.2.1
	FS station antenna height	Marginally increases the radio horizon, but has negligible impact when aircraft altitude is significantly higher than FS station elevation ($h_{AC} \gg h_{FS}$).	Low	3.2.1
	FS station antenna elevation	Provides higher antenna off-axis discrimination towards FS stations for higher elevation angles. Mainly impacts the operation at low aircraft latitudes with GSO networks.	High	2.4.6
	Antenna off-axis performance	Antenna reference pattern for FS stations differs only in the main lobe. Difference in RFI caused by respective FS transmit power and in the antenna main lobe.	Medium	2.4.6
	Bandwidth	Higher levels of interference power due to larger number of FS station having frequency overlap. Is determined by IFE link budget.	Medium	2.4.9
	Polarization	FS RFI discrimination up to 1.4 dB, if opposite linear polarization used. Not considered as FS and SATCOM use both polarizations	Low	2.4.8

Table 7: Summary of system parameters influencing the channel gain between interfering terrestrial fixed service stations and aeronautical satellite communication receivers - Part II

System element	Parameter	Dependencies / Impact	Relevance	Section
Radiowave propagation	Free space path loss	Attenuation of FS interference increasing with higher aircraft flight altitude due to longer slant ranges in the air-to-ground path	High	2.4.1
	Atmospheric losses	Minor attenuation of FS interference due to atmospheric gases (clear-sky) considered. The attenuation due to rain and clouds, which adds the highest atmospheric attenuation levels in the wanted and interfering paths, is not correlated. Thus, considering rain in only one path is overly conservative.	Low	2.4.3
	Multipath	Specular reflections and MPCs do not significantly influence the aggregate FS RFI in a plane-Earth model, with the LOS component remaining dominant. If non-plane-Earth conditions or reflections from buildings are considered, stronger multipath components could occur; however, these would generally coincide with shadowing of the LOS path, thereby reducing its contribution.	Low	2.3.2, 2.3.3
	Doppler Effect	Doppler effect leads to a uniform frequency shift across the signal bandwidth. As $f_D \ll B_{AC}$, the channel exhibits frequency-flat fading characteristics. Any occurring fading affects the entire signal spectrum equally, leading to amplitude variations without significant distortion of frequency components.	Low	2.4.4
	Clutter, Diffraction	Not present in the air-to-space path for a plane-Earth model. Effects are related to buildings and vegetation at low flight altitudes and are therefore negligible for high-altitude operation.	Low	2.4.10

3 The *AERO-FS* Interference Model

3.1 Simulation Model

To thoroughly simulate the behavior of the interference from terrestrial FS stations into an A-ESIM receiver, a detailed geometric simulation model is developed. This model, which is independent of frequency, is adaptable for various frequency bands, including Ku-, K- and Ka-bands and can also be used for other aeronautical applications such as narrow band links and even for non-GSO systems, as long as the specific technical and operational parameters of each component (aircraft, FS, propagation...) are appropriately defined. A schematic of the developed simulation model is depicted in Fig. 26.

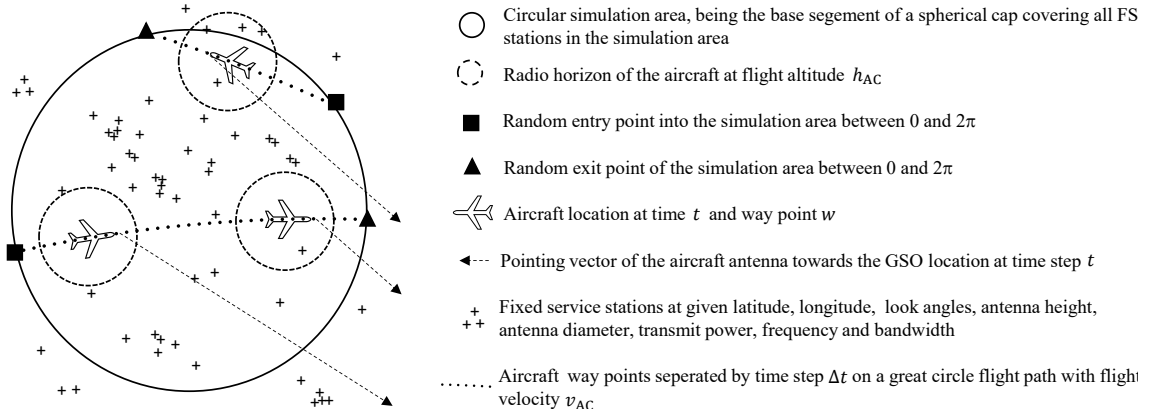


Figure 26: Schematic representation of the developed simulation model for aggregate fixed service radio frequency interference into an aeronautical satellite communications receiver.

The model aims to realistically reflect the interference environment of an A-ESIM while remaining general enough to cover a broad spectrum of FS deployments. To this end, the terrestrial FS component is defined once using ITU-R recommended technical and operational characteristics, including the quantity and location of FS stations, antenna heights, diameters, look angles, center frequencies, transmit powers, and bandwidths. This deterministic setup is fixed throughout the simulation, which offers a more realistic representation than Monte Carlo approaches that lack temporal detail.

The aircraft operations are modeled separately, encompassing a circular area of operation that covers the FS deployment area. The considered flight trajectory assumes the aircraft is in the en-route flight phase, where it follows a great circle, simulating the flight path of a typical commercial aircraft providing IFE services. This entails minimal directional, altitude, or velocity adjustments.

The associated GSO space station and the Earth are moving with the same angular rate, respectively, the Earth and the GSO space station rotate with an angular rate of $\omega_e = 4.178\,074\,582\,3 \cdot 10^{-3}$ deg. Hence, an Earth-centered, Earth-fixed (ECEF) coordinate system is used, where all FS stations, the aircraft, and the GSO network can be represented by their three-dimensional

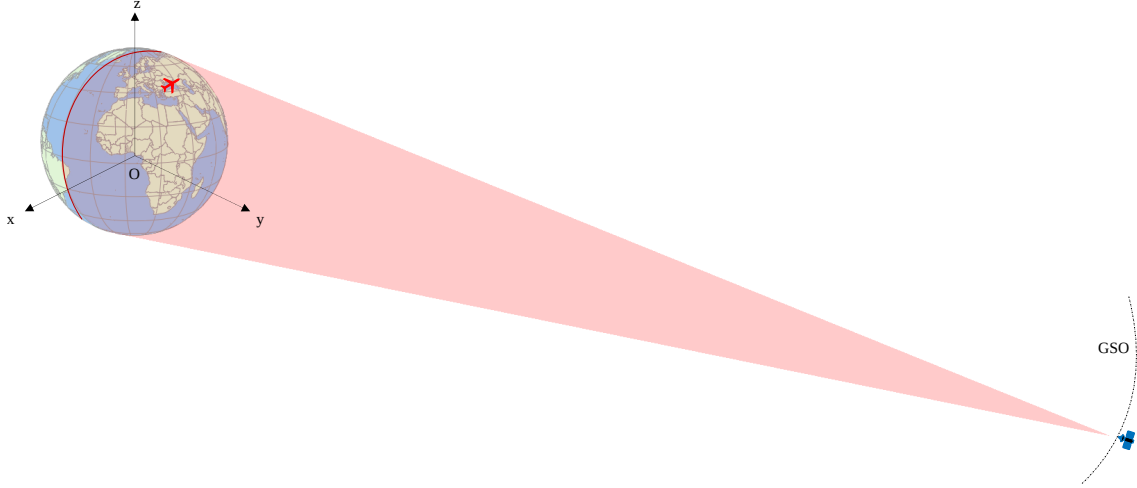


Figure 27: Reference Cartesian coordinate system for the *AERO-FS* interference model, illustrating local origin O at the center of the Earth, an aircraft, the geostationary satellite orbit, and the field of view of a space station in that orbit.

Cartesian coordinates originated in the center of the Earth, as depicted in Fig. 27. The positioning vector of all elements in the simulation, i.e., the FS stations, the aircraft and the GSO satellite are describes in Cartesian coordinates

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (r_E + h) \cos(\text{Lat}) \cos(\text{Lon}) \\ (r_E + h) \cos(\text{Lat}) \sin(\text{Lon}) \\ (r_E + h) \sin(\text{Lat}) \end{bmatrix}. \quad (3.1)$$

Lat and Lon are the coordinates of the particular elements on the surface of the Earth and h denotes the associated height of the respective object above the surface of the Earth (h_{AC} , h_{FS} and h_{GSO}). The radius of the GSO is defined according to ITU-R S.1503-4 $r_{GSO} = 42\,164.2$ km, hence $h_{GSO} = r_{GSO} - r_E = 35\,786.055$ km. The spatial angles between vectors, required, for example, to compute off-axis antenna gain, Doppler shifts, and other direction-dependent effects are calculated using the scalar product of their normalized Cartesian representations. An exemplary angle θ between two vectors $\vec{a}$ and $\vec{b} \in \mathbb{R}^3$ is given by

$$\theta = \arccos \left(\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| \cdot |\vec{b}|} \right). \quad (3.2)$$

The pointing directions of the FS antennas, defined by elevation and azimuth angles, are first transformed into the local ENU coordinate system at each FS station and subsequently converted into the global Cartesian ECEF coordinate system.

The simulation is initiated by selecting two random points between 0 and 2π . These points define the entry of the aircraft into and the exit of the aircraft out of the simulation area. The flight path is then calculated as the orthodromic line between these two points

according to (2.47). Afterward, the flight path between the entry and the exit point is divided into a total number of W way points according to the selected time step Δt and flight velocity v_{AC} defining the number of simulation samples for one simulated flight through the simulation area.

$$W = \frac{d_{\text{ortho}}(\text{Lat}_a, \text{Lon}_a, \text{Lat}_e, \text{Lon}_e)}{v_{AC}} \Delta t. \quad (3.3)$$

At each waypoint w out of in total W waypoints, those M FS stations are identified, which are located inside the radio horizon of the aircraft receiver (i.e. $d_m^r \leq d^{\text{RH}}$) and, secondly, exhibit frequency overlap with the aircraft receiver bandwidth. With these identified stations, the observed aggregate discrete time-variant LOS FS RFI power is calculated as

$$\zeta[l] = \sum_{m=1}^{M[l]} a_m^{\text{LOS}}[l] \sum_{f=f_l}^{f_h} \frac{\text{psd}_m^{\text{I}}}{a_m^{\text{tot}}(f)}, \quad (3.4)$$

where f_l is the lower end of the occupied bandwidth and f_h is the upper end of the overlapping bandwidth. The overlapping bandwidth B_m^o of the aircraft receiver with the m th FS station is calculated by (2.58) where the total attenuation of both filters is less than 25 dB, i.e. $B_m^o = \{f : a_B^{\text{tot}} < 25 \text{ dB}\}$. a_m^{LOS} is the channel gain of the interfering m th LOS component according to (2.41). The channel gain for each interfering path incorporates the elements outlined in section 2.4, tailored to the specific geometric conditions at each waypoint w of the aircraft's trajectory, respectively, at the simulation sample l out of a of total R samples. To compute the channel gain, all instantaneous spatial angles and distances are calculated to quantify the off-axis gains and losses between the aircraft and FS station, which are within the radio horizon and exhibit frequency overlap.

This process is repeated for each waypoint until the simulation area's exit point is attained. Subsequently, new random entry and exit points are generated, leading to the recalculation of waypoints in conjunction with the associated LOS FS RFI, continuing this iteration until the desired number of simulation samples is reached. The described steps for the complete simulation are schematically shown in a flowchart in Fig. 28.

The accuracy of the model is influenced by the chosen time step Δt and the duration of the simulation. These parameters should be selected to ensure that the highest interference levels are detected and that all geometric conditions are adequately represented. With the simulation considering only the LOS component of the FS RFI, without accounting for any fast fading effects, the necessary time step to capture the highest interference events can be derived from the geometric relationships between the aircraft and the FS stations, as well as from the technical and operational characteristics involved. Appendix B of

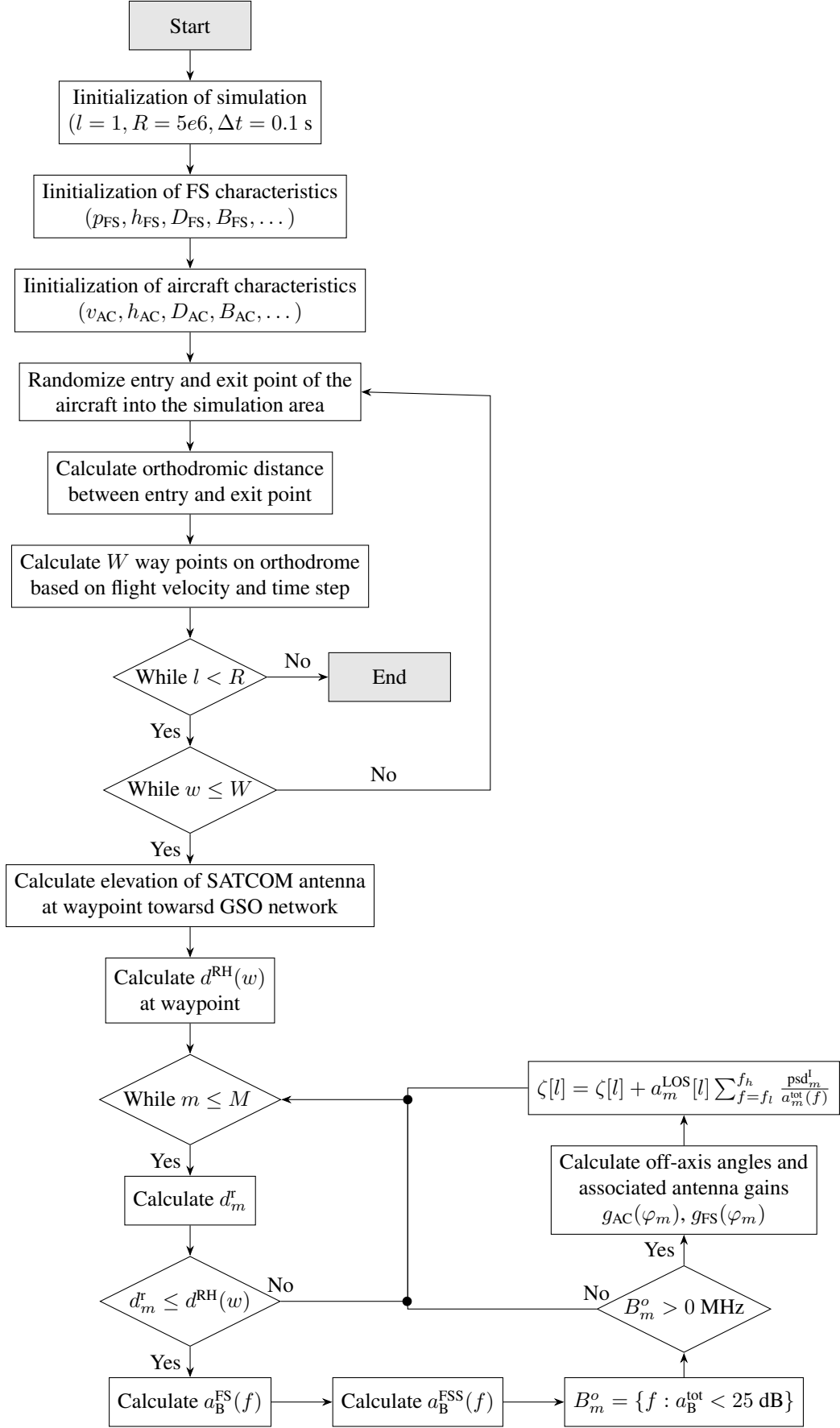


Figure 28: Schematic flow diagram of the *AERO-FS* interference model for generating a time series of fixed service radio frequency interference power levels ζ

Table 8: Core parameters and configuration requirements for the *AERO-FS* interference simulation model

Parameters	Symbol	Unit	Value
Time step	Δt	s	0.1
Number of samples	R		5 000 000
Accuracy	ΔG	dB	0.5

this thesis proposes a generic algorithm for determining the required time step Δt based on these geometric conditions to achieve the desired accuracy for the LOS FS RFI. The presented algorithm illustrates that the required accuracy depends on several factors, including the FS antenna reference pattern, the aircraft's flight velocity, flight altitude, maximum FS station antenna elevation, and maximum FS station antenna height. By utilizing this algorithm with the selected FS characteristics, an accuracy of $\Delta G = 0.5$ dB is attained with a time step of $\Delta t = 0.1$ s.

The simulation will capture a total of $R = 5e^6$ samples, which would detect interference levels of probability down to $p = 2 \cdot 10^{-5} \%$. This number of samples ensures high statistical robustness so that the outcomes can be confidently interpreted, providing convergence of the underlying statistics. An increased sample size enhances the reliability of the results, making it possible to draw more accurate conclusions from the data. A larger data set provides greater statistical significance and expands the capacity for post-processing. At low probabilities ($10^{-5}\%$), the highest interference events are captured, which are short-term and could severely affect the SATCOM link. Moreover, the number of data points is sufficient to sample a variety of locations in the reference area. This approach ensures comprehensive coverage and mitigates the risk of repeating the same geometries multiple times. All important simulation parameters are summarized in Table 8.

Key Takeaway

The developed *AERO-FS* simulation framework models aggregate FS RFI into an aeronautical SATCOM receiver with high geometric and temporal resolution, using a deterministic, frequency-independent setup of FS deployments and realistic aircraft trajectories. Employing Cartesian ECEF coordinates and explicitly calculating off-axis gains, distances, and frequency overlaps at each waypoint, the model produces statistically robust interference time series (down to $p = 2 \cdot 10^{-5}\%$) while maintaining general applicability to K-, and Ka-band links.

3.2 Input Characteristics

The accuracy and reliability of the simulation build the basis for the applicability of the derived results. A trade-off is made between realistic data from existing networks, systems, deployment from a particular region, applications, and generic data. Hence, the model elements are modeled with a combination of ITU-R recommended parameters and existing technical and operational characteristics.

3.2.1 Fixed Service Interference Characteristics

The modeling of the FS station deployment in combination with the respective link characteristics is one of the significant challenges of the simulation. The deployment, structure, and utilization of terrestrial FS differ country-by-country due to distinct international allocations, regional harmonization, and national usage. Furthermore, specific information on using the FS in each country is limited, and administrations are not obligated to publish information on spectrum usage for FS in their territory. Accordingly, most administrations do not report their national FS deployments.

For the model developed, the available ITU-R Recs. [31, 60, 51] are used, reflecting typical technical and operational characteristics based on contributions of several notifying administrations. The model shall cover various FS deployments that represent global usage. Required parameters that are not provided in ITU-R Recs. are complemented by information from FS stations recorded in the MIFR. In particular, information on the spatial distribution of FS stations and, respectively, the FS density over more extensive areas is not provided in any current ITU-R Recs.. The FS density varies country-by-country and is correlated to the population density and infrastructure, such as cities and highways. To reflect these distributions, geospatial data of FS stations from France are used, which have voluntarily reported their FS deployments to ITU-R and represent a relatively dense use of terrestrial FS in Europe.

In particular, the distribution of FS terminals in the considered frequency range is taken from the ITU-R MIFR [64] for terrestrial services. At the time of generation of this simulation, an instantaneous number of 24 226 FS links in a comparably large area ($551\,695\text{ km}^2$) was recorded, providing a sound basis for statistical assessments. Information on the locations of the FS stations (latitudes and longitudes), the center frequencies, and bandwidths is extracted from this database. Fig. 29 plots the spatial distribution of FS stations and recorded FS links in the central territory of France according to the MIFR, which is used in the simulation.

Besides the location and density of the FS station, the allocation of center frequencies and bandwidths is important. Not every frequency within the band 17.7-19.7 GHz can be allocated to an FS station. Meanwhile, FS stations' use of spectrum follows the regional

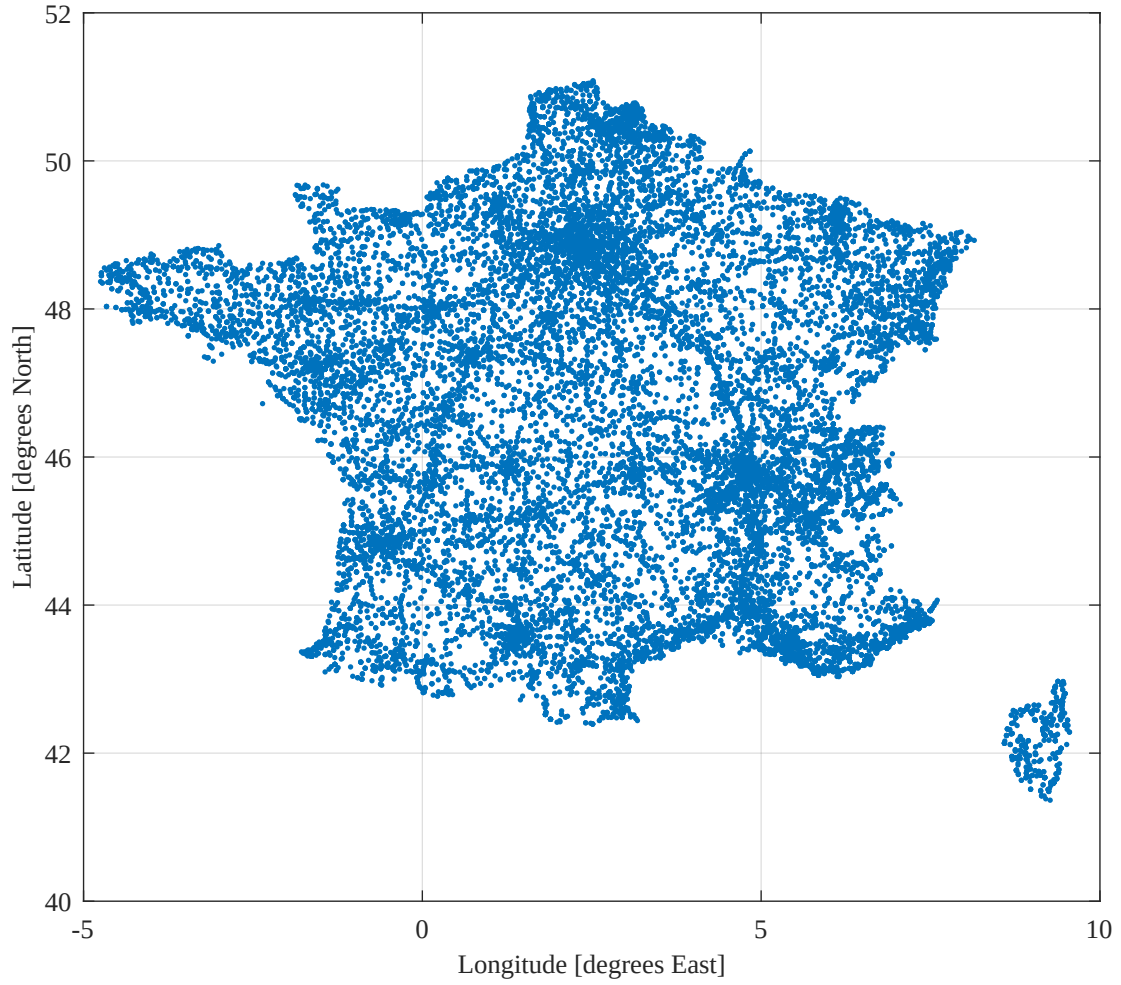


Figure 29: Spatial distribution of fixed service links within the territory of France, as recorded in the Master International Frequency Register for the frequency range 17.7-19.7 GHz, illustrating the correlation between fixed service station density and infrastructure elements such as cities, roads, and highways.

harmonization plan set out in [58] [59] which is depicted in Fig. 23. Using the recorded information of FS links, including frequency and bandwidth assignments tied to specific geographic locations, the model ensures that multiple frequencies allocated to a single FS station are preserved, and that no self-interference between co-located FS stations occurs. Incorporating this information prevents unrealistic scenarios arising from a purely random (Monte Carlo) allocation of frequencies and bandwidths, which would not be representative when implemented in the model.

Table 9: Technical and operational characteristics of the fixed service, extracted from Recommendations ITU-R F.758-7 and ITU-R F.2086-0.

Parameters	Unit	Range and distribution
Modulation		$\mathcal{U}\{\text{QPSK}, 64\text{-QAM}\}$
Equivalent isotropically radiated power	dBW	$EIRP = \begin{cases} \mathcal{U}(-4.4, 43) & \text{for QPSK} \\ \mathcal{U}(-1.1, 33) & \text{for 64-QAM} \end{cases}$
Antenna gain	dBi	$G_{FS} = \begin{cases} \mathcal{U}(21.7, 48.3) & \text{for QPSK} \\ \mathcal{U}(32, 45) & \text{for 64-QAM} \end{cases}$
Antenna pattern		Rec. ITU-R F.1245
Feeder loss	dB	$A_{FL} = \begin{cases} \mathcal{U}(0, 2) & \text{for QPSK} \\ \mathcal{U}(0, 9.3) & \text{for 64-QAM} \end{cases}$
Tx output power	dBW	$P_I = \begin{cases} \mathcal{U}(-37, -3) & \text{for QPSK} \\ -10 & \text{for 64-QAM} \end{cases}$
Antenna azimuth	degrees	$\Lambda_{FS} = \mathcal{U}(0, 360)$
Antenna elevation	degrees	$\varepsilon_{FS} = \mathcal{N}(0.02, 2.69)$
Antenna height	m	$h_{FS} = \mathcal{N}(29, 17.84)$
Modeled FS links		24 226
Latitude	degrees North	According to MIFR
Longitude	degrees East	According to MIFR
Center frequencies	MHz	According to MIFR
Bandwidth	MHz	According to MIFR

The remaining parameters for the geometric part of the simulation – the antenna heights h_{FS} and the antenna look angles (ε_{FS} and Λ_{FS}) – are based on the input from several notifying administrations providing ranges and statistical distributions recommended in [60]. The FS link power levels are also taken from the recommended characteristics of FS links by ITU-R [31]. This Rec. provides typical ranges of output power p^I , feeder losses A_{FL} , and antenna gains G_{FS} .

Table 9 summarizes the characteristics of the FS stations applied in the model. For the simulation, the FS characteristics are assigned to the FS links once, being kept constant throughout the whole simulation.

3.2.2 Aircraft Characteristics

The technical and operational characteristics of the aircraft that influence the received FS RFI are chosen to be aligned with the available and applicable ITU-R Recs. and Reps. for typical FSS links and A-ESIMs. The maximum flight altitude and flight velocity differ depending on the aircraft type. The selected flight velocity and flight altitude in the model are typical for commercial aircraft in the en-route flight phase, covering the majority of flights and thus ensuring a broad coverage of flight scenarios. The cruising altitude for long distances is between 30 000 and 36 000 ft [18]. Therefore, an aircraft flight altitude of $h_{AC} = 10$ km, corresponding to 32 800 ft, is used. The flight velocity is also selected to be $v_{AC} = 500$ kts, corresponding to 926 km/h, the typical speed of modern aircraft [18].

Table 10: Technical and operational characteristics of the aeronautical earth station in motion and its associated satellite receiver considered in the simulation.

Parameters	Unit	Value
Flight altitude	km	$h_{AC} = 10$
Flight velocity	kts	$v_{AC} = 500$
Centre frequency	GHz	$f_c = 17.8$
Receive bandwidth	MHz	$B_{AC} = 20$
Receive noise	K	$T_N = 184$
Antenna diameter	m	$D_{AC} = \begin{cases} 0.3 & \text{for } D_{AC}/\lambda < 50 \\ 0.9 & \text{for } D_{AC}/\lambda \geq 50 \end{cases}$
Antenna pattern		Rec. ITU-R S. 580-6
Antenna elevation	degrees	$\varepsilon_{AC} \geq 15$
Antenna diameter	m	$D_{AC} = \{0.3, 0.9\}$
GSO satellite longitude	degrees East	$L_{GSO} = 63$
GSO radius	km	$r_{GSO} = 42\,164.2$

Higher speeds would require a higher sampling rate, respectively, a shorter time step, to capture the highest interference events; thus, it is not favorable to simulate the maximum speed. It is more desirable to achieve the scaling of the model to different flight velocities.

The rotational symmetric antenna reference pattern of Recommendation ITU-R S.580-6 represents the SATCOM antenna and is simulated for two diameters: $D_{AC} = 0.3$ m resulting in a $D_{AC}/\lambda < 50$ and $D_{AC} = 0.9$ m for $D_{AC}/\lambda \geq 50$.

The corresponding GSO satellite is arbitrarily chosen to be the Inmarsat GX1 satellite located at 63 degrees East, which is a K-, Ka-band satellite providing global IFE services. The orbit location of 63 degrees East results in a relatively low antenna elevation of the aircraft SATCOM antenna over Europe of about $\varepsilon_{AC} \geq 15$ degrees, the typical lower bound of SATCOM GSO operations in the K- and Ka-bands. Thus, a conservative approach is ensured.

A typical bandwidth for IFE service is assumed to be $B_{AC} = 20$ MHz, which is based on the feasible IFE LBs (see Table 2).

The center frequency of the aircraft receiver is chosen not to be the center frequency of the considered band 17.7-19.7 GHz. In Fig. 23, it is shown that for the regional harmonization, a frequency gap exists at 18.7 GHz to separate the "go" and "return" links. Choosing this frequency would not reflect the real situation of FS RFI. The data in the MIFR shows a nearly uniform distribution of the center frequencies in the 17.7-18.5 GHz band; thus, a low center frequency of $f_c = 17.8$ GHz is chosen. It is, therefore, desirable to develop a correction factor for scaling the results to different center frequencies.

All relevant parameters used in this simulation for the aircraft part of the system are summarized in Table 10.

Key Takeaway

The input characteristics combine ITU-R-recommended parameters with real-world technical and operational data to ensure realism and general applicability. The FS part is based on geospatial deployment data from the MIFR for France and preserving actual frequency assignments to avoid unrealistic self-interference. The information of the MIFR is complemented by technical parameters from ITU-R Recs., including EIRP ranges, antenna patterns, and antenna heights. The aircraft part reflects typical commercial en-route operation for K- and Ka-band GSO link at 17.8 GHz with 20 MHz bandwidth and antenna patterns from ITU-R S.580-6. The geometry is conservatively set for low antenna elevations, ensuring robust performance estimates under realistic and challenging conditions.

3.3 Simulation Results

The results of the geometric simulation for multiple flights across the simulation area with different D_{AC}/λ values are processed in this section. A snap-shot of a selected time-series of ζ is shown in Fig. 30 for the two selected reference antenna diameters and a period of 100 minutes out of a total of 138.89 hours of simulated flight time corresponding to five million samples at $\Delta t = 0.1$ s. These diagrams show that the aggregate LOS FS RFI varies up to 40 dB for both antenna diameters. Some high LOS FS RFI signal levels could last from several seconds up to several minutes, depending on the speed of the aircraft above ground. Furthermore, a zoom into the plot in Fig. 31 supports the conclusion from section 2.3.1, that in the aggregate FS RFI case, the highest interference events follow the shape of FS antenna gain pattern of the dominant interfering station

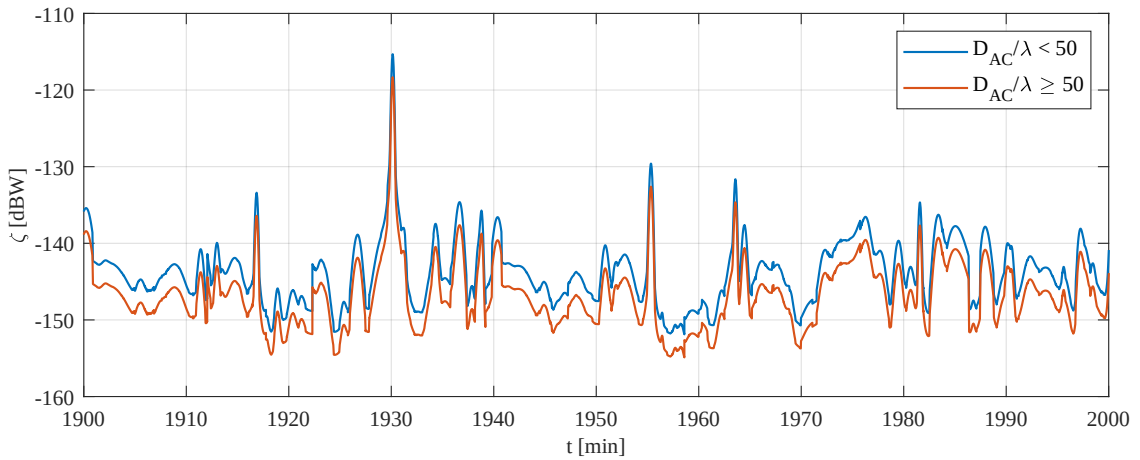


Figure 30: Time series of aggregate line-of-sight fixed service radio frequency interference power levels for an arbitrarily chosen period of 100 minutes, illustrating the time-variant behavior and variations of up to 40 dB.

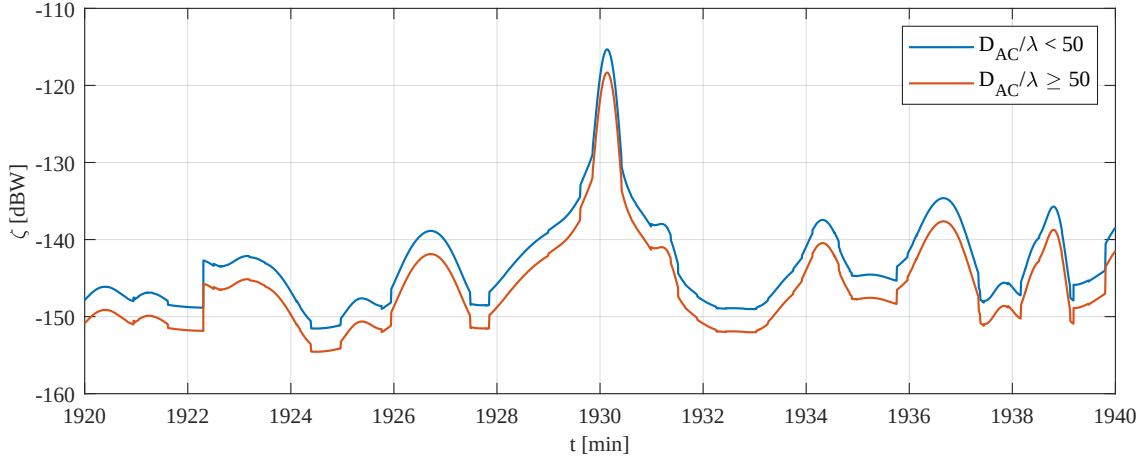


Figure 31: Zoom of a time series of aggregate line-of-sight fixed service radio frequency interference power levels for an arbitrarily chosen period of 20 minutes, illustrating the time-variant behavior following the shape of the fixed service station antenna pattern.

In order to verify the correctness of the simulation, the difference between the FS RFI values for both antenna diameter $\Delta\zeta = \zeta(D_{AC}/\lambda < 50) - \zeta(D_{AC}/\lambda \geq 50)$ curves for both of the aircraft antenna diameter should vary according to the used antenna pattern of Rec. ITU-R S.580-6 in maximum at an off-axis angle $\varphi = 10$ degrees by

$$\begin{aligned}\Delta G_{\max} &= 52 - 10 \log_{10} D/\lambda - 25 \log_{10} \varphi - (29 - 25 \log_{10} \varphi) \\ &= 23 - 10 \log_{10} D/\lambda \\ &= 10.5 \text{ dB},\end{aligned}\tag{3.5}$$

and minimum at $\varphi = 180$ degrees off-axis angle by

$$\begin{aligned}\Delta G_{\min} &= 10 - 10 \log_{10} D/\lambda - (-10 \text{ dBi}) \\ &= 20 - 10 \log_{10} D/\lambda \\ &= 7.5 \text{ dB}.\end{aligned}\tag{3.6}$$

This difference can be observed when subtracting the derived values of ζ for both curves. A histogram of the derived results confirming the correct simulation is shown in Fig. 32 for all five million samples. It shows that the difference between the two selected reference antenna diameters is not constant and varies between 7.5 and 10.5 dB. This range confirms the correct setup of two simulations as the off-axis gain of the Rec. S.508-6 differs for the two selected D_{AC}/λ . It also verifies that most of the contributions from FS RFI are caused by the far sidelobes of the FS antennas, and only a limited number of interference cases exist, which are at the minimum off-axis angles of the A-ESIM antenna at 15 degrees.

The LOS FS RFI shown in Figs. 30 and 31 can be characterized as a slowly changing process on a large scale, comparable to a shadowing process. Such large-scale variations are typically caused by geometry-dependent factors, such as the gradual change in antenna pointing angles and the variation of path loss with distance, rather than by fast multipath fading. Consequently, the statistical behavior of the LOS FS RFI is more likely to follow a log-normal distribution, which is commonly used to model large-scale shadowing, instead of small-scale fading models such as Rayleigh or Rician, which assume rapid variations due to multipath propagation. For a comprehensive characterization of this slow-varying behavior, it is therefore appropriate to determine the first- and second-order statistics of ζ and to fit them against suitable large-scale fading models (e.g., log-normal or Suzuki processes).

3.3.1 First and Second Order Statistics

First-order statistics are the pdf and the related cumulative distribution function (cdf). The pdfs of the aggregate LOS FS RFI power ζ are determined from the simulated data using the kernel density estimation (KDE) method introduced in [65]. The estimated pdf using the KDE is expressed as

$$\hat{f}(x) = \frac{1}{nu} \sum_{i=1}^n K\left(\frac{x_0 - x_i}{u}\right). \quad (3.7)$$

Here, x_0 is the reference value for density estimation, and x_i is the i^{th} sample out of n

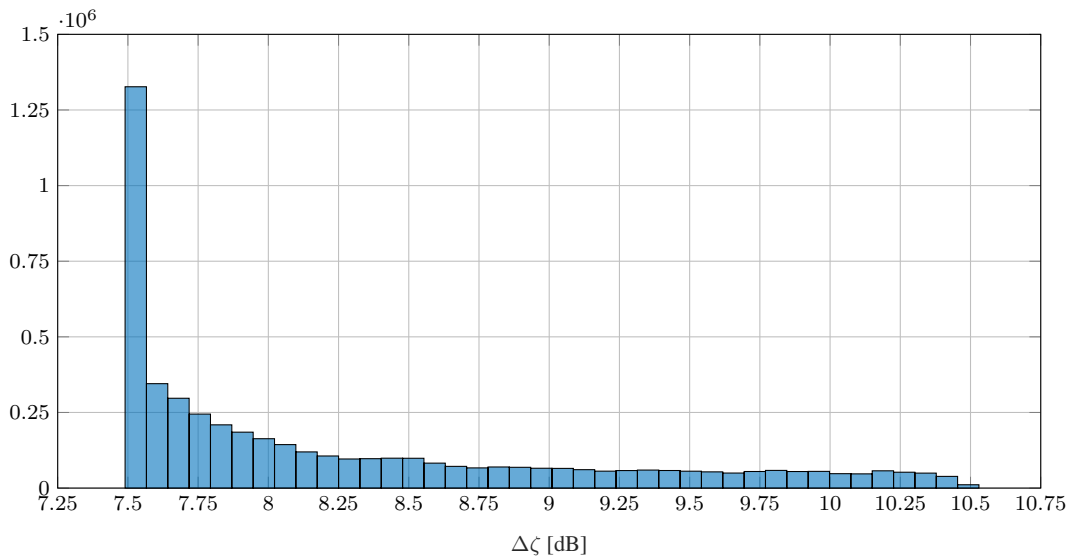


Figure 32: Histogram of the difference between the simulation data of the two reference antenna diameter not exceeding the range of $\Delta\zeta \in \{7.5...10.5\}$

samples. $K(\cdot)$ can be an arbitrary pdf and is chosen to be the Gaussian kernel which is expressed by

$$K(s) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}s^2\right), \quad (3.8)$$

with $s = (x_0 - x_i)/u$. The bandwidth u is a scaling parameter that controls the smoothness of the density estimate. Silverman's rule of thumb [66] is used to estimate the optimal bandwidth u that minimizes the mean integrated squared error. It can be applied if the kernel and the data distribution are of Gaussian shape. The histograms of the simulated samples in each scenario, from which one example is presented in Fig. 33, exhibit a Gaussian shape in the logarithmic domain. Hence, u can be estimated for the KDE application in the logarithmic domain by

$$u = \left(\frac{4\sigma^5}{3n}\right)^{\frac{1}{5}}, \quad (3.9)$$

where σ is the standard deviation of the logarithmic values $\sigma = \sqrt{\text{Var}(\ln(x_i))}$.

The resulting pdf derived by the application of the KDE in the natural logarithmic domain is presented in Fig. 33 and the corresponding cdfs are presented in Fig. 34. The pdf derived by the KDE algorithm matches the histogram of the corresponding simulated samples very well.

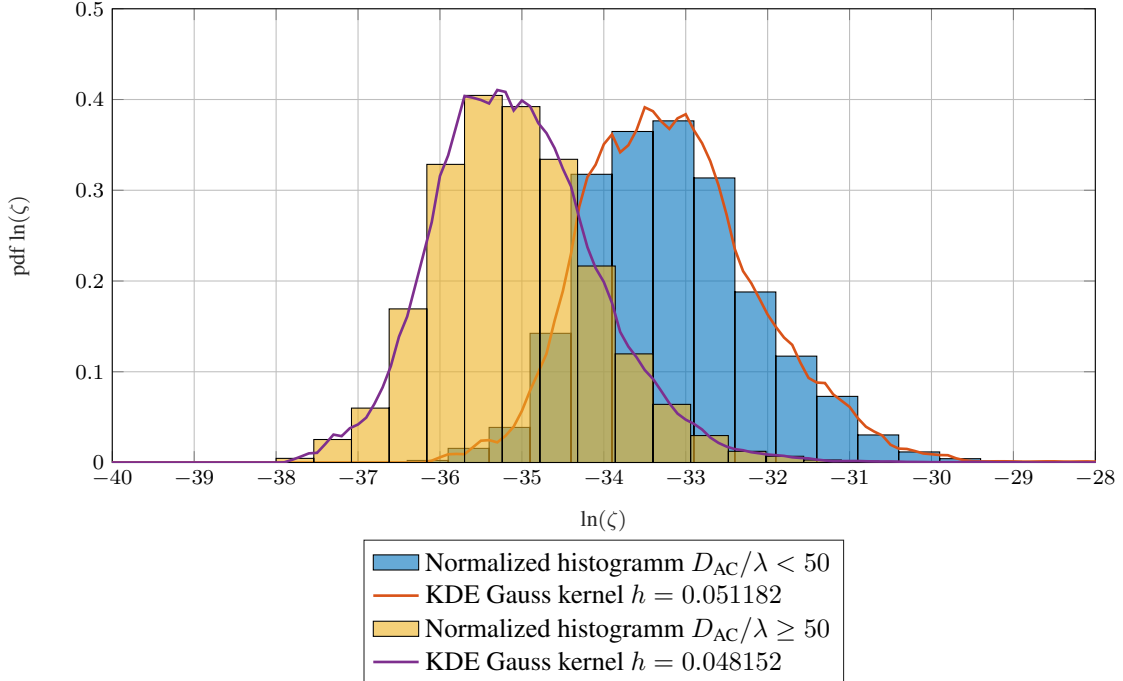


Figure 33: Comparison between the probability density function obtained via kernel density estimation and the corresponding histogram of the simulated samples.

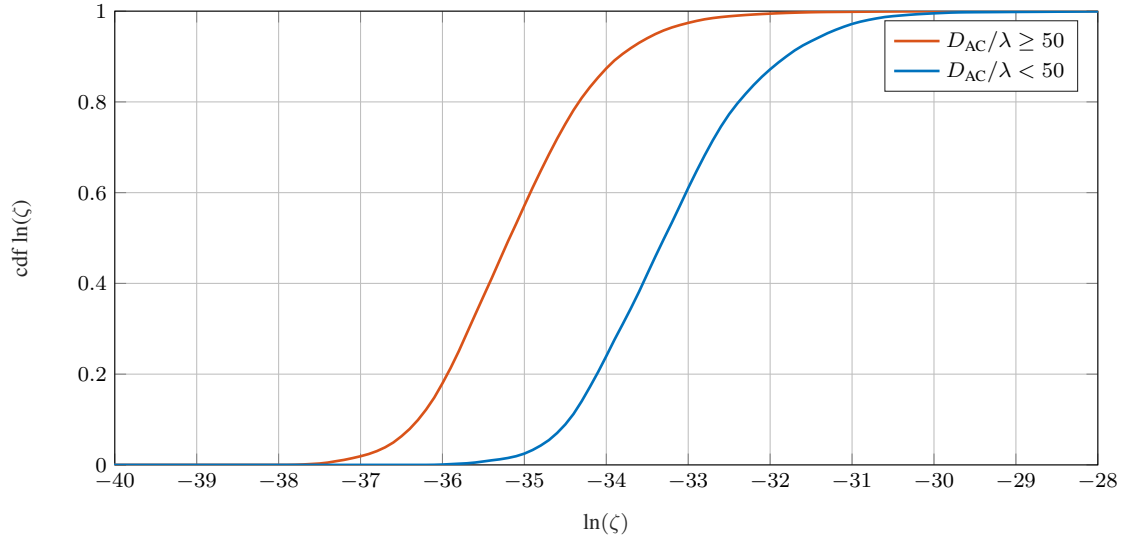


Figure 34: Cumulative distribution function of ζ for the two simulated antenna diameters.

The second-order statistics, in particular the level crossing rate (LCR) and the average duration of fades (ADF), characterize the temporal behavior of interference events. Once the link is interrupted or the RFI level exceeds a given threshold, these metrics indicate how often such threshold crossings occur and the average time the RFI remains above (or below) this level. According to [67], the LCR is the expected rate at which the received LOS FS RFI crosses a specified level in the positive direction, while the ADF is given by the ratio of the cdf to the corresponding LCR. Since these statistics depend on the aircraft's flight velocity, the LCR and ADF are normalized to the maximum Doppler frequency $f_{D, \max}$, making them independent of v_{AC} . Figures 35 and 36 present the resulting second-order statistics for the two simulated aircraft antenna diameters.

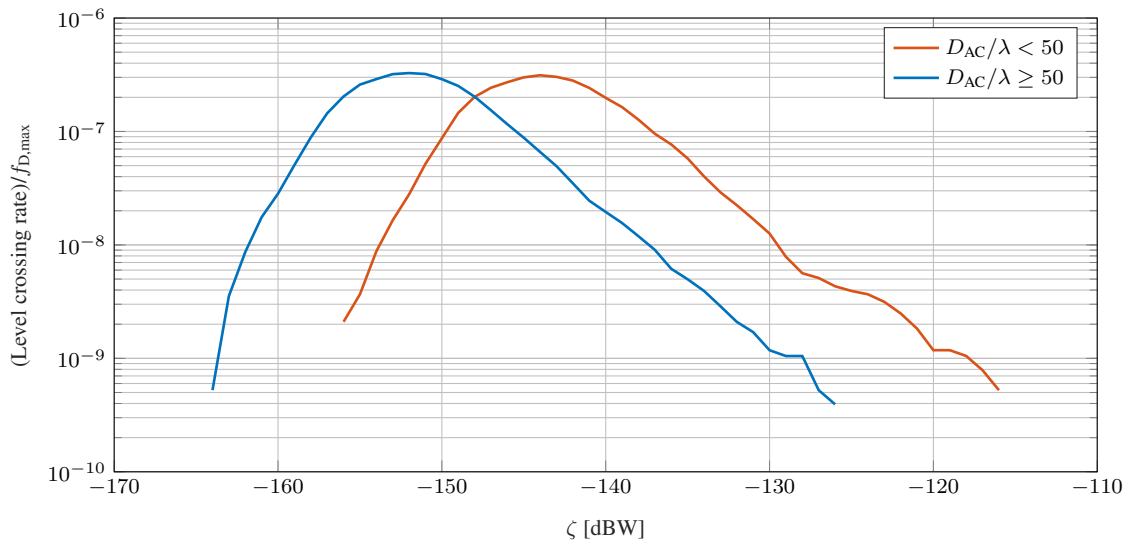


Figure 35: Level crossing rate normalized to the maximum Doppler frequency as a function of ζ

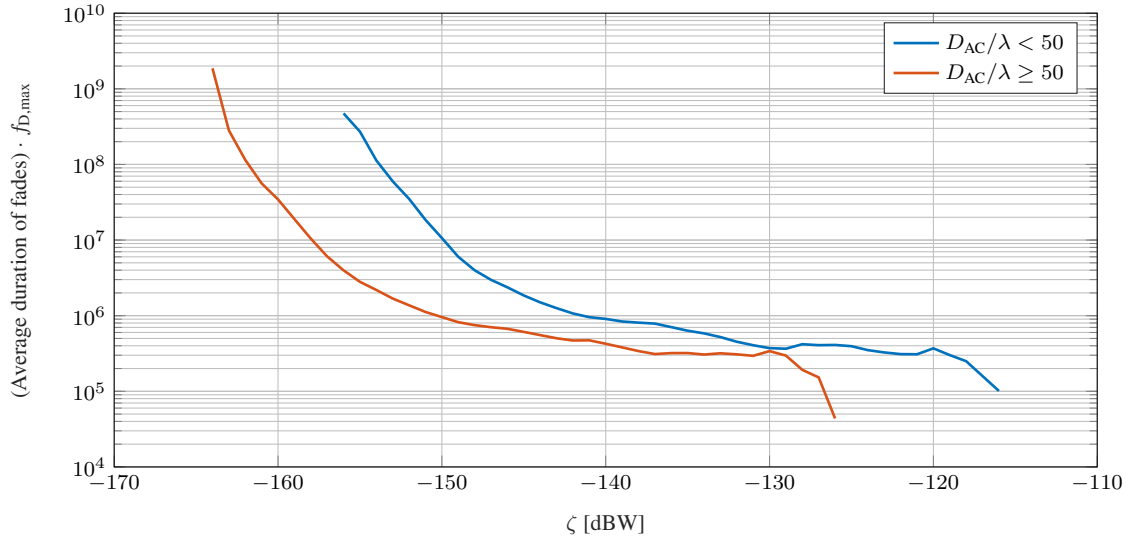


Figure 36: Average duration of fades normalized to the maximum Doppler frequency as a function of ζ

3.3.2 Log Skew Normal Distribution Fitting

For statistical assessments, it is desirable to model the pdf of the FS RFI without simulating the interference. Those distribution can be used for availability assessments, by, e.g., convolving the pdf of the interference with the pdf of other time-variant parameters when those parameters can be considered as uncorrelated and independent random variables.

The pdfs shown in Fig. 33 exhibit an asymmetrical skew-normal (SN) distribution in the natural logarithmic domain, which is inconsistent with the symmetrical shape expected for a log-normal or Suzuki distribution. A single entry FS RFI into the aircraft, whose channel is underlying a shadowing process, which is comparable to the behavior of the FS RFI, could be described by a log-normal (LN) distribution of the mean signal power. Multiple independent LN-distributed RFI signals would result in a sum of independent LN distributions. In the absence of a closed-form expression for the sum of LN distributions, the pdf of the aggregate signal can be fitted by a log-skew-normal (LSN) distribution [68].

Wu et al. propose in [69] to approximate the LN sum distributions by an LSN distribution, which fits the observed shape of the determined pdfs. The LSN provides the exact relation between linear and logarithmic domains like the LN and normal distribution. Hence, the relation between LSN and an SN distribution is $\text{LSN} = e^{\text{SN}}$. The pdf of the SN distribution is given by

$$\text{pdf}_{\text{SN}}(x) = 2\phi(x)\Phi(\alpha x) \quad (3.10)$$

where $\phi(x)$ is the pdf of the normal distribution

$$\phi(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (3.11)$$

and $\Phi(x)$ is the cdf of the normal distribution

$$\Phi(x) = \int_{-\infty}^x \phi(t) dt = \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{x}{\sqrt{2}}\right) \right]. \quad (3.12)$$

The cdf of a SN distribution is defined by

$$\operatorname{cdf}_{\text{SN}}(x) = \Phi(x) - 2T(x, \alpha), \quad (3.13)$$

where $T(\cdot, \cdot)$ denotes Owens' T function. To add location and scale parameters to the pdf and cdf, x can be transformed to $\frac{x-\xi}{\omega}$, where ξ denotes the location, ω the scale, and α the shape of the SN distribution. Knowing these parameters allows the cdf and the pdf of the SN distribution to be determined. Following the approach of [69], these parameters can be calculated from the expected value, variance, and skewness of the SN distribution, which Azzalini gives in [70] and are derived from the moment generating function. Specifically, the expected value is given by

$$\mu = \xi + \omega\delta\sqrt{2/\pi} \quad (3.14)$$

with $\delta = \alpha/\sqrt{1+\alpha^2}$. The variance of the SN distribution is

$$\sigma_{\text{SN}}^2 = \omega^2(1 - 2\delta^2/\pi) \quad (3.15)$$

and the skewness of the SN distribution can be determined by

$$\gamma_1 = \frac{4 - \pi}{2} \frac{(\delta\sqrt{2/\pi})^3}{(1 - 2\delta^2/\pi)^{3/2}}. \quad (3.16)$$

By solving eq. (3.14), (3.15) and (3.16) with respect to α , ω , ξ and δ , the following equation for the shape of the SN distribution are obtained

$$\alpha = \delta/\sqrt{1 - \delta^2}. \quad (3.17)$$

The scale ω of the SN distribution can be calculated by

$$\omega = \sqrt{\frac{\sigma_{\text{SN}}^2}{(1 - 2\delta^2/\pi)}}, \quad (3.18)$$

the location ξ of the SN distribution is determined by

$$\xi = \mu - \delta\omega\sqrt{2/\pi}, \quad (3.19)$$

with

$$\delta = \sqrt{\frac{b^{2/3}}{1 + (2b^{2/3}/\pi)}}, \quad (3.20)$$

where

$$b = \frac{2\gamma_1}{(4 - \pi)\sqrt{2/\pi}^3}. \quad (3.21)$$

By applying the method of moments introduced by Pearson in [71] μ , σ_{SN} , and γ_1 can be obtained using the simulated samples. For a pdf, the moment of the first order is related to the mean value, the second order is related to the variance σ , and the third order is related to the skewness of a pdf. These values are determined for a total number of R simulated samples by

$$\mu = \frac{1}{R} \sum_{i=1}^R x_i \quad (3.22)$$

$$\sigma_{\text{SN}}^2 = \frac{1}{R} \sum_{i=1}^R (x_i - \mu)^2 \quad (3.23)$$

$$\gamma_1 = \frac{\frac{1}{R} \sum_{i=1}^R (x_i - \mu)^3}{\left(\frac{1}{R-1} \sum_{i=1}^R (x_i - \mu)^2 \right)^{3/2}}. \quad (3.24)$$

The result for applying the SN approximation compared with the pdf derived by the KDE for the selected antenna diameters are plotted in Fig. 37. They exhibit excellent match, providing a mean squared error (MSE) of less than 10^{-4} . The known relation between the logarithmic and linear domains is applied to provide an analytic description of the cdf and the pdf of the LSN in the linear domain. With the LSN distribution being determined by three parameters, which are location ξ , scale ω , and shape α , the LSN cdf is defined by

$$\text{cdf}_{\text{LSN}}(x) = \int_{-\infty}^{\ln(x)} 2\phi_{\mathcal{N}}\left(\frac{x - \xi}{\omega}\right) \Phi_{\mathcal{N}}\left(\alpha \frac{x - \xi}{\omega}\right) dt \quad (3.25)$$

Here, $\phi_{\mathcal{N}}(x)$ denotes the pdf of the normal distribution

$$\phi_{\mathcal{N}}(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (3.26)$$

and $\Phi_{\mathcal{N}}(x)$ is the cdf of the normal distribution

$$\Phi_{\mathcal{N}}(x) = \int_{-\infty}^x \phi_{\mathcal{N}}(t) dt = \frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{x}{\sqrt{2}}\right) \right]. \quad (3.27)$$

The pdf is the first derivative of the cdf and can, therefore, be calculated by

$$\text{pdf}_{\text{LSN}}(x) = \frac{1}{x} 2\phi_{\mathcal{N}}\left(\frac{\ln(x) - \xi}{\omega}\right) \Phi_{\mathcal{N}}\left(\alpha \frac{\ln(x) - \xi}{\omega}\right). \quad (3.28)$$

The results of the approximation of the LSN distribution for the simulation data in terms of ξ , ω , and α are presented in Table 11 separated for the values of D_{AC}/λ . As additional information, the 99th percentile of ζ is provided in the last column.

Table 11: Parameters of the log skew normal distribution for two different antenna diameters

D_{AC}/λ	α	ω	ξ	99 th percentile of ζ
< 50	2.4672	1.5696	-34.321	-132.9 dBW
≥ 50	2.2492	1.4524	-36.1219	-141.6 dBW

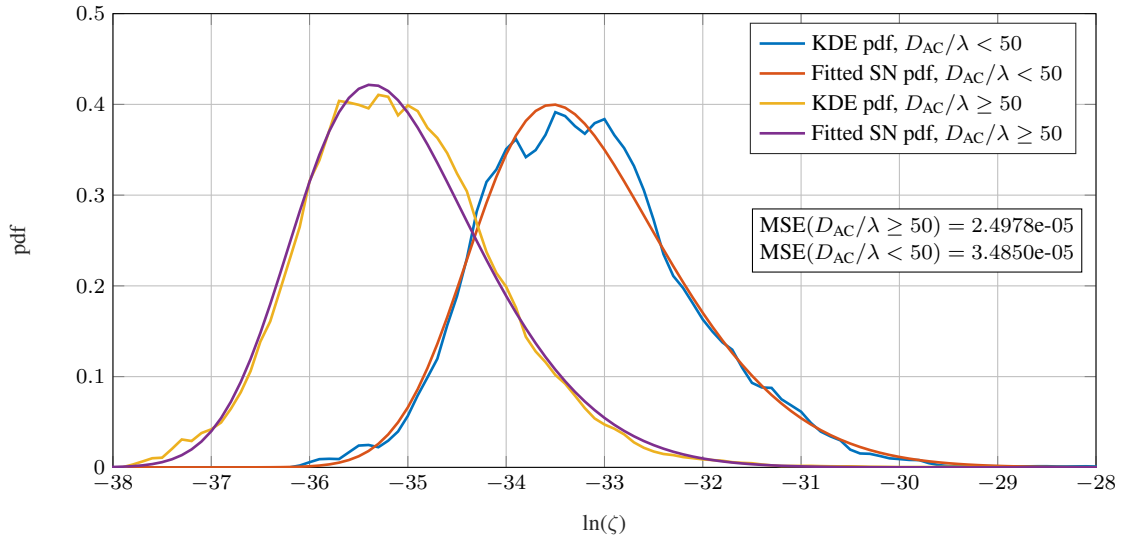


Figure 37: Probability density functions of the training sequence compared with the fitted skew-normal distribution, illustrating the asymmetry of the empirical distribution in the natural logarithmic domain.

Key Takeaway

The log-skew-normal distribution provides an accurate, closed-form representation of the FS RFI probability density function, enabling reliable statistical modeling without needing full-scale simulations. Commonly used distributions such as Rice, Rayleigh, log-normal, or Suzuki fail to capture the asymmetry and tail behavior observed in the derived data. Based on simulated samples, the LSN parameters, location, scale, and shape, are obtained via the method of moments, allowing analytic evaluation of the pdf and cdf in logarithmic and linear domains.

3.3.3 Performance Degradation

To put the simulation results into context and show the significance of the FS RFI, the performance degradation on the considered IFE link is assessed. In aeronautical communications, the performance of a link is defined by three parameters – availability, continuity, and integrity [72].

- (1) Availability determines the probability of a link accessing a specific spectrum. When the spectrum is not accessible, the link is unavailable.
- (2) The continuity provides information on how long the spectrum is usable until the link is interrupted.
- (3) The integrity is related to the performance of the accessed spectrum, which is quantifiable in terms of bit error ratio of the received signal.

In terms of availability, the first performance criterion, Fig. 38 shows the complementary cdf of the INR, i.e., the probability ($\Pr$) that a certain INR, calculated according to (2.54), is exceeded.

Whether or not the link is protected and which unavailability of the link is acceptable can be examined from two perspectives. From the regulatory point of view, there is no protection criterion for FSS from time variant interference in the K- and Ka-bands due to the uncommon use of mobile earth stations in the FSS (c.f. section 1.2). Rec. ITU-R S.1432 [73] provides an FSS protection criterion for GSO applications in a time-invariant interference environment. It recommends that the interference allowance of co-primary allocated radio services sharing the same frequency bands shall not exceed 6% of the system noise corresponding to an $\text{INR} = -12.2$ dB. Rec. ITU-R S.1323 [74] provides a protection criterion for time-variant interference sources from other satellite systems.

It states that the internetwork interference caused by the earth and space station emissions of all other satellite networks operating in the same frequency band that can po-

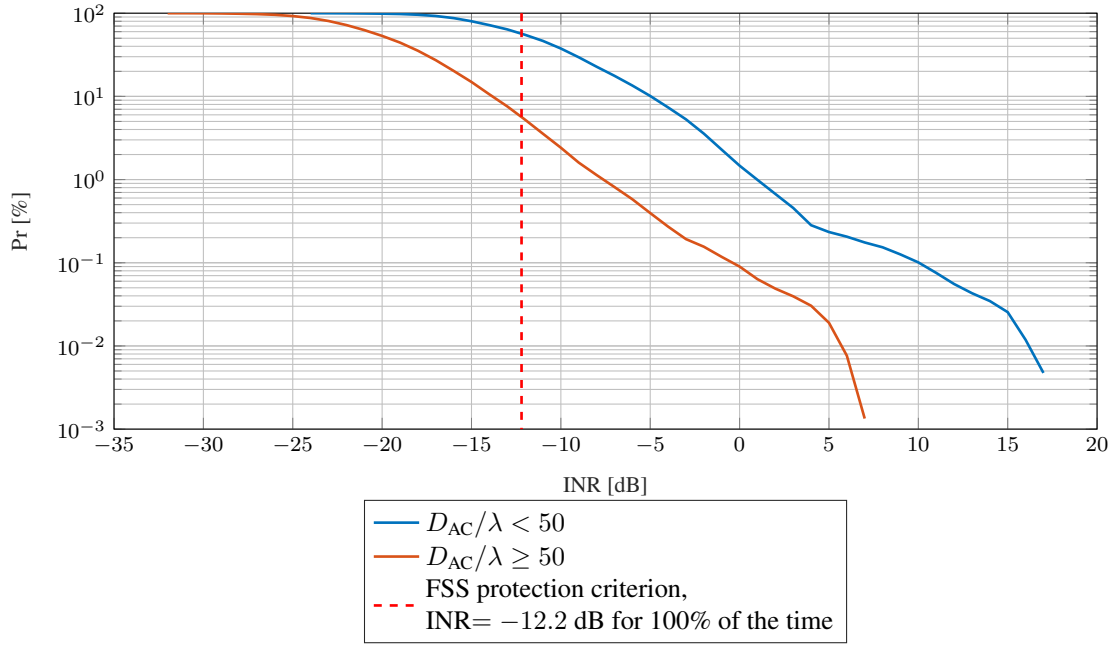


Figure 38: Unavailability of an aircraft receiver as a function of the acceptable interference-to-noise ratio

tentially cause interference of a time-varying nature, should be responsible for at most 10% of the time allowance for the SNR value specified in the short-term performance objectives of the desired network and correspond to the shortest percentage of time.

In the case of networks using adaptive coding, the internetwork interference shall be responsible for at most a 10% decrease in the amount of reserve capacity available to links that require heavier coding to compensate for rain fading, on the assumption that the network maintains, with the use of this reserve capacity the same level of performance as it did with no time-varying interference present.

Hence, a particular performance objective is required, which varies with the satellite, the provider, and the respective link characteristics, especially when considering the coordination between networks. Furthermore, the concept of reserved capacity is not fully defined; thus, the reduction in performance is of more interest, which is also provided in the same Recommendation.

Fig. 38 evaluates the INR statistics and includes the protection criterion of $\text{INR} = -12.2 \text{ dB}$. This regulatory threshold is exceeded by 54.5% of the time for $D_{AC}/\lambda < 50$ and 5.2% for $D_{AC}/\lambda \geq 50$. The high exceedance and the difference between the two curves demonstrate the significant influence of the antenna diameter and the off-axis performance in the aircraft SATCOM antenna.

Though regulatory limits protect a radiocommunication service and not a particular link or application, calculating the absolute link degradation Y_L is another metric to determine the impact. The link degradation metric is also provided in Rec. ITU-R S.1323 and is

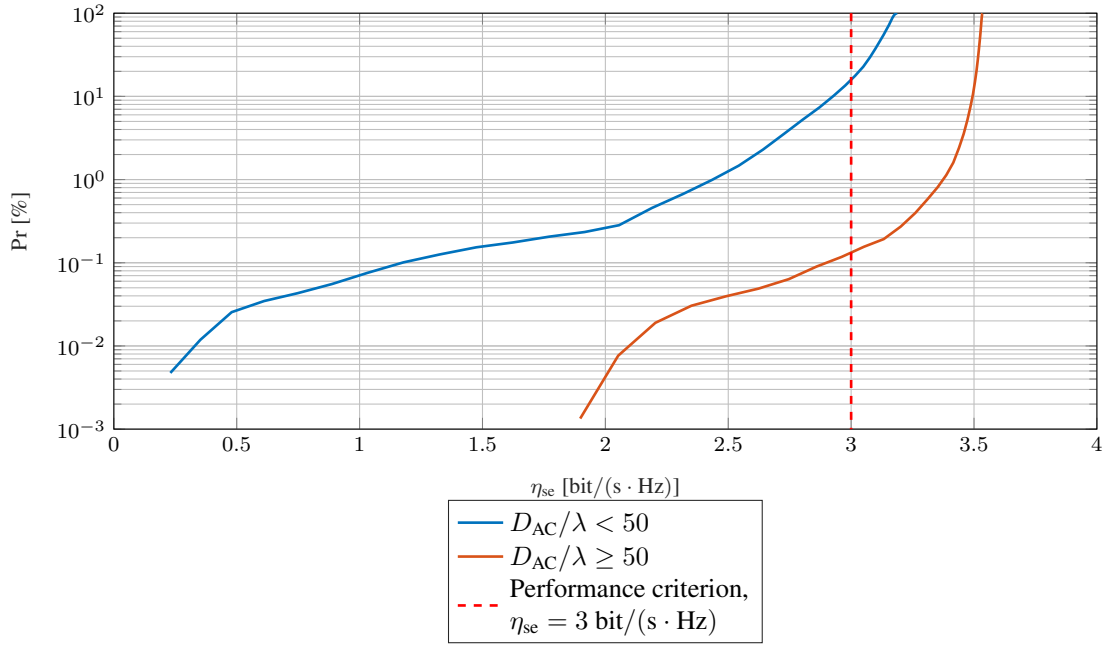


Figure 39: Spectral efficiency of the in-flight entertainment link, as calculated in Table 2, after accounting for fixed service radio frequency interference

determined in Annex 1 Part 1 Methodology A. It is calculated as the division between the SNR and SINR. The relationship can be expressed as

$$Y_L = \frac{\text{SNR}}{\text{SINR}} = \frac{p_{\text{rx}}^{\text{GSO}}}{k_B T_N B_{\text{AC}}} \cdot \frac{k_B T_N B_{\text{AC}} + \zeta}{p_{\text{rx}}^{\text{GSO}}} = \frac{k_B T_N B_{\text{AC}} + \zeta}{p_{\text{rx}}^{\text{GSO}}} = 1 + \frac{\zeta}{k_B T_N B_{\text{AC}}}. \quad (3.29)$$

The link degradation Y_L does not depend on the signal level of the wanted path $p_{\text{rx}}^{\text{GSO}}$, but only on the characteristics of the A-ESIM SATCOM receiver and the FS RFI. When using the initial IFE LBs calculated in Table 2 for both network, and setting the required spectral efficiency of $\eta_{\text{se}} = 3 \text{ bit}/(\text{s} \cdot \text{Hz})$ as a performance threshold, this value is exceeded, respectively, falls below that value for the IFE satellite having an A-ESIM terminal with $D_{\text{AC}}/\lambda < 50$ for 17.6% of for the interfering satellite operating an A-ESIM terminal with $D_{\text{AC}}/\lambda \geq 50$ for 0.15% of the time.

Table 12: Level crossing rate and average fade duration associated with error performance degradation, defined by an interference-to-noise ratio $\text{INR} > -12.2 \text{ dB}$ and a spectral efficiency of the in-flight communications link below $\eta_{\text{se}} = 3 \text{ bit}/(\text{s} \cdot \text{Hz})$.

D_{AC}/λ	INR > -12.2 dB		$\eta_{\text{se}} = 3 \text{ bit}/(\text{s} \cdot \text{Hz})$	
	LCR [s^{-1}]	ADF [s]	LCR [s^{-1}]	ADF [s]
< 50	0.004572	121.4	0.00356	46.5
≥ 50	0.001344	40.0	0.00009	17.0

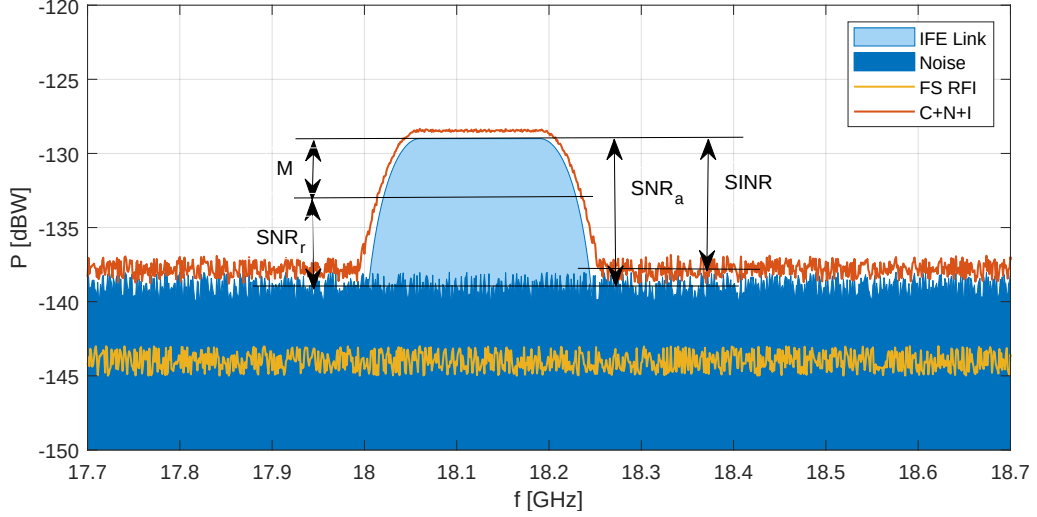


Figure 40: Exemplary spectrum plot for an in-flight entertainment link at the aircraft receiver

Table 12 provides the information on continuity in terms of LCR and ADF for the ITU-R protection criterion of the FSS and the performance criterion. If the FS RFI increases the noise floor by 6%, the average duration for the simulated flight velocity that stays above this level is two minutes for antennas with $D_{AC}/\lambda < 50$. This situation occurs 16.5 times per flight hour. For antennas with $D_{AC}/\lambda \geq 50$, the average duration is 40 s, which occurs 4.8 times per flight hour. Regarding the reduction of spectral efficiency, the average duration threshold exceeded for $D_{AC}/\lambda < 50$ is 46.5 s, which occurs 12.8 times per flight hour. Similarly, for the $D_{AC}/\lambda \geq 50$, the average duration is 17 s, which occurs only 1 time every 3 hours. For smaller aircraft having less flight speed, the duration increases and, respectively, the occurrence of interference events decreases. A larger SATCOM antenna decouples the FS RFI more than a smaller SATCOM antenna. Moreover, operating A-ESIMs with GSO networks using a larger aircraft SATCOM antenna elevation reduces the FS RFI signal levels.

From a system design perspective, a higher link margin must be provisioned if interference is not compensated at the signal processing level. Advanced techniques such as interference rejection combining [75] or cooperative spectrum strategies like "Writing on dirty paper" or the generation of interference maps [76, 77] can mitigate interference effectively, but in their absence, additional margin is needed to maintain link reliability.

The maximum permissible INR INR_p for the IFE SATCOM link, required to accommodate all FS interference levels within the available link margin m_L , can be determined by considering the signal relations illustrated in Fig. 40. The maximum tolerable FS interference level is directly dependent on the available link margin. Specifically, the difference between the available SNR_a and the resulting SINR must be greater than or equal

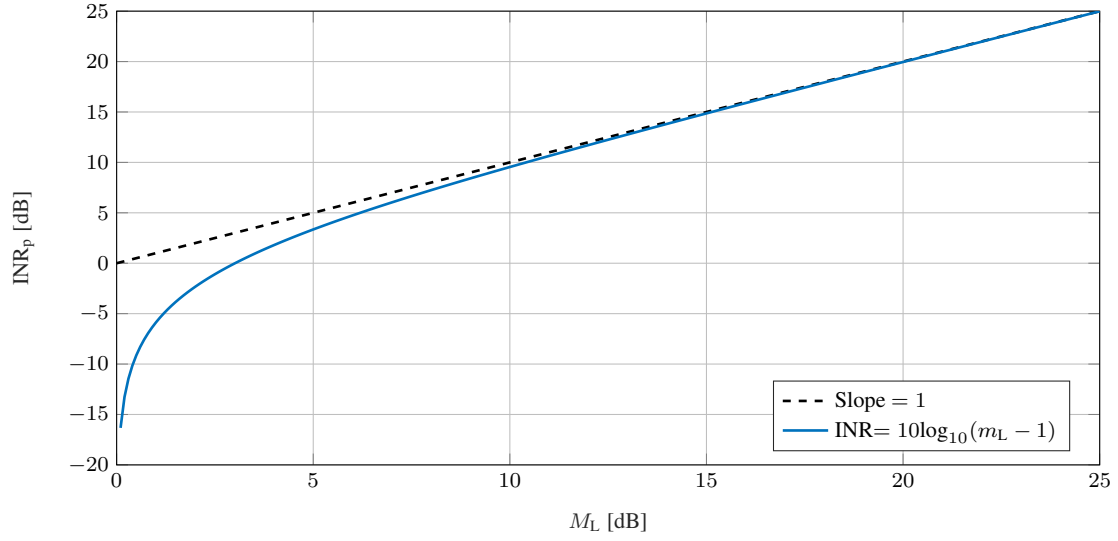


Figure 41: Maximum permissible interference-to-noise ratio as a function of the available link margin

to the link margin:

$$\text{SNR}_a - \text{SINR} = M_L. \quad (3.30)$$

Expressed in linear terms, this condition becomes:

$$\frac{p_{\text{rx}}}{\eta} \cdot \frac{\eta + \zeta}{p_{\text{rx}}} = m_L \quad (3.31)$$

By eliminating p_{rx} in (3.31) and solving for the link margin m_L , the link margin is obtained:

$$m_L = \frac{\zeta}{\eta} + 1, \quad (3.32)$$

which leads to a direct relationship between the permissible interference and the available link margin. Rewriting this in logarithmic form provides the maximum permissible interference-to-noise ratio, INR_p :

$$\text{INR}_p = 10 \log_{10}(m_L - 1) \quad (3.33)$$

This expression allows translating the available link margin into a maximum allowable interference power level, as illustrated in Fig. 41. Combining the above findings, the effect of FS RFI on the delicate balance between coordinated GSO networks, as initially presented in Table 2 in section 1.2.2, is now re-evaluated under the influence of FS RFI. This reassessment considers a moderate simulated interference level of $\text{INR} = 0$ dB, which can be scaled to different antenna diameters and frequencies using the conversion factors introduced in section 4.5.

Table 13: Link budget calculation for two geostationary satellite networks providing in-flight entertainment to aircraft with different terminal sizes, considering the impact of fixed service radio frequency interference.

Parameter	Abbreviation	Unit	IFE satellite	Interfering satellite
Priority			No	Yes
Equivalent isotropically radiated power spectral-density limit	EIRP-SD	dB(W/Hz)	-20	-15
Speed of light in vacuum	c_0	m/s		299 792 458
Frequency	f	GHz	18	18
Elevation	ε_{AC}	deg.	15	15
Radius of the Earth	r_E	km		6 378.145
Radius of the geostationary satellite orbit	r_{GSO}	km		42 164.2
Distance	d	km	40 060.78	40 060.78
Free space path loss	a_L	dB	209.6	209.6
Antenna diameter	D_{AC}	m	0.9	0.45
Antenna gain	g_{AC}	dBi	42.7	36.7
Receive noise temperature	T_N	K	190	190
Orbit separation	φ	deg.		2
Antenna pattern			Rec. ITU-R S.580-6 [21]	
Off-axis gain	$g_{AC}(\phi)$	dB	21.5	21.5
Signal-to-adjacent satellite interference ratio	SIR_{ASI}	dB	16.2	20.2
FS interference-to-noise ratio	INR_{FS}	dB	4.8	1.8¹
Boltzmann's constant	k_B	dB(J/K)		-228.6
Signal-to-noise ratio	SNR	dB	18.9	17.9
Signal-to-interference-plus-noise ratio	SINR	dB	11.2	13
Spectral efficiency [22]	η_{se}	bit/(s · Hz)	2.5	2.9
Required link margin to compensate FS RFI	M_L	dB	3.1	1.4

The extended link budget in Table 13 demonstrates a substantial reduction in spectral efficiency due to FS interference. In the worst case, an additional link margin of up to 3.1 dB is required to compensate for this degradation and maintain the desired performance level.

Increasing transmit power is not feasible due to existing coordination agreements between satellite network operators. That increase may even exceed the regulatory pfd-limits defined in Article 21.16 of the ITU-RR, which should protect terrestrial services. Moreover, preemptively including a margin to account for this type of interference can significantly affect coordination outcomes and reduce the efficient use of spectrum. Most important practices are not permitted under resolves 1.1.2 of Res. 169 (WRC-23), which explicitly states that ESIMs shall neither cause more interference nor claim more protection than typical earth stations operating in geostationary fixed-satellite service networks. Hence, interference mitigation measures at the signal processing level could improve the situation if improved aircraft antenna characteristics cannot be considered.

¹ Application of (4.33): $INR_{FS} = INR + 10 \log_{10} (D_2 f_2) - 97.3$, which evaluates to $INR_{FS} = 0 \text{ dB} + (0.45 \text{ m} \cdot 18 \text{ GHz}) - 97.3 = 1.8 \text{ dB}$

Key Takeaway

FS RFI degrades the IFE SATCOM links across all three ICAO-defined service quality dimensions, availability, continuity, and integrity, causing the spectral efficiency to fall below typical performance objectives. Preemptively including additional margin to account for such interference can significantly influence coordination outcomes and reduce the efficient use of spectrum. However, Res. 169 (WRC-23) strictly prohibits ESIMs from causing more interference or claiming more protection than typical GSO FSS earth stations, limiting mitigation options. When improving antenna characteristics on the aircraft is not feasible, only signal processing and level mitigation remain viable to preserve link integrity and regulatory compliance.

3.3.4 Variation in Flight Altitude

Section 2.4.1 analyzed the impact of the flight altitude on single-entry FS RFI. To extend these findings, the simulation is repeated for multiple flight altitudes, considering aggregate LOS FS RFI, as this effect is critical for realistic performance assessment. This section discusses the derived first- and second-order statistics of FS RFI, based on results obtained via KDE and an approximation using the LSN distribution.

From the KDE-derived pdfs in Fig. 42, the following observations can be made regarding the behavior of the aggregate FS RFI power as a function of flight altitude. With increasing aircraft altitude h_{AC} , the location of the pdf shifts to higher values. This shift results from the expanding visibility area of the aircraft, which encompasses a larger number of FS stations, especially within the back lobe of the aircraft's receive antenna. Although higher altitudes lead to increased propagation loss in interfering paths, tending to reduce the RFI, the growing number of contributing FS stations offsets this effect. Few FS stations are within radio visibility at lower altitudes, leading to a lower aggregate noise floor. Consequently, the location parameter of the pdf reflects a lower range of received power values compared to higher flight altitudes.

In addition to this shift, the scale of the pdf decreases with altitude. This is primarily due to the larger distances between the aircraft and the FS stations at higher altitudes, which increase propagation losses and reduce the power of dominant interferers. The scale of the LSN distribution is influenced by the dynamic range between the highest interference, typically caused by high-EIRP FS stations at worst-case angles into the aircraft antenna main lobe, and the cumulative background noise contributed by off-axis FS stations in the antenna back lobe. While the geometry and EIRP of the strongest interferers tend

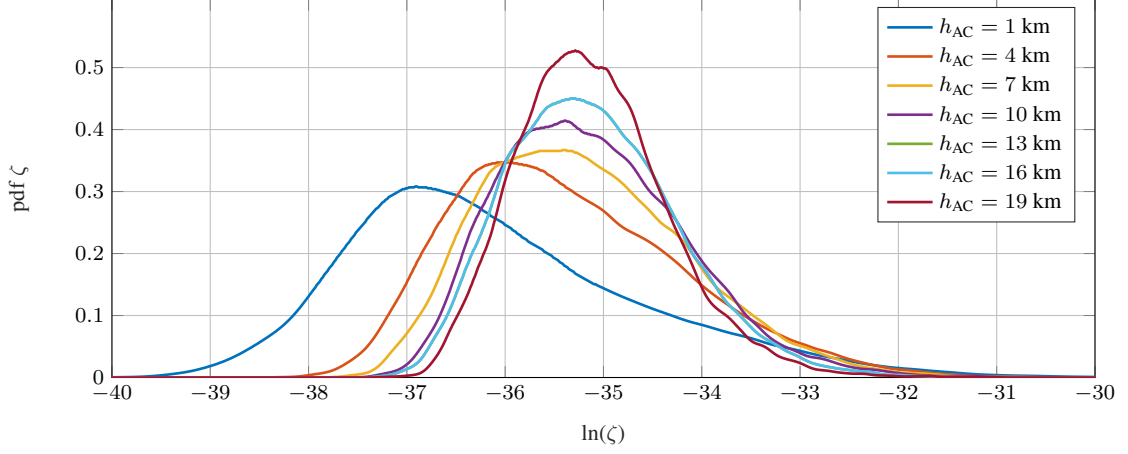


Figure 42: Probability density functions of $\ln(\zeta)$ for different aircraft flight altitudes h_{AC} .

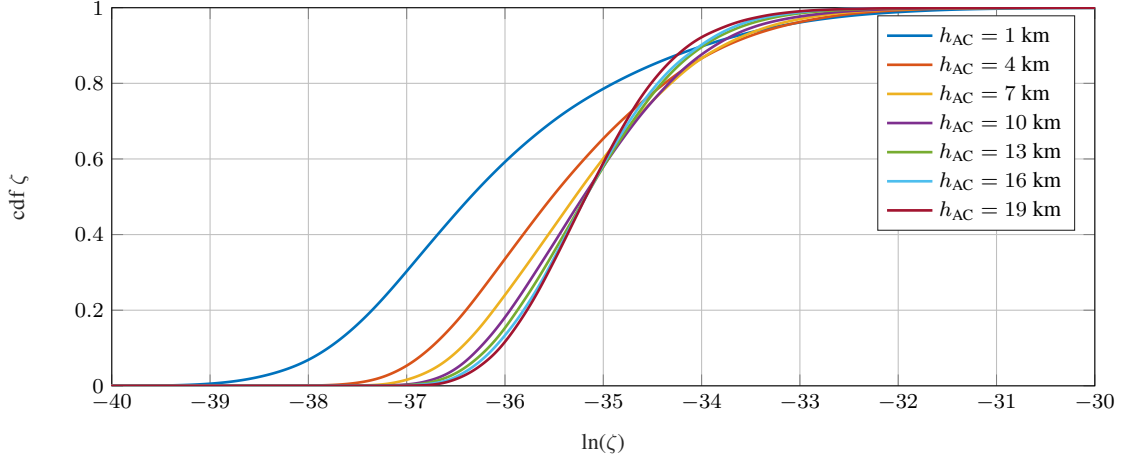


Figure 43: Cumulative distribution functions of $\ln(\zeta)$ for different aircraft flight altitudes h_{AC} .

to remain similar across altitudes, the absolute received power levels decrease due to additional path loss. Simultaneously, the aggregate back-lobe noise floor increases with altitude due to the expanded visibility area. This combination leads to a narrower overall distribution and thus a reduced scale.

The KDEs-derived pdfs and corresponding cdfs for multiple flight altitudes are illustrated in Fig. 42 and Fig. 43. The second order statistics ADF and LCR as a function of flight altitude are shown in Fig. 44 and Fig. 45, respectively.

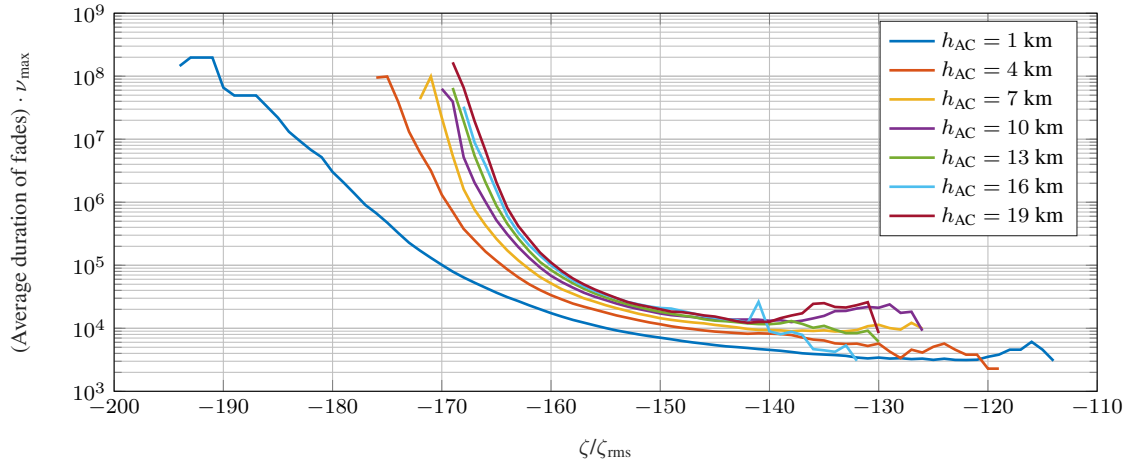


Figure 44: Average duration of fades of ζ/ζ_{rms} for different aircraft flight altitudes h_{AC} .

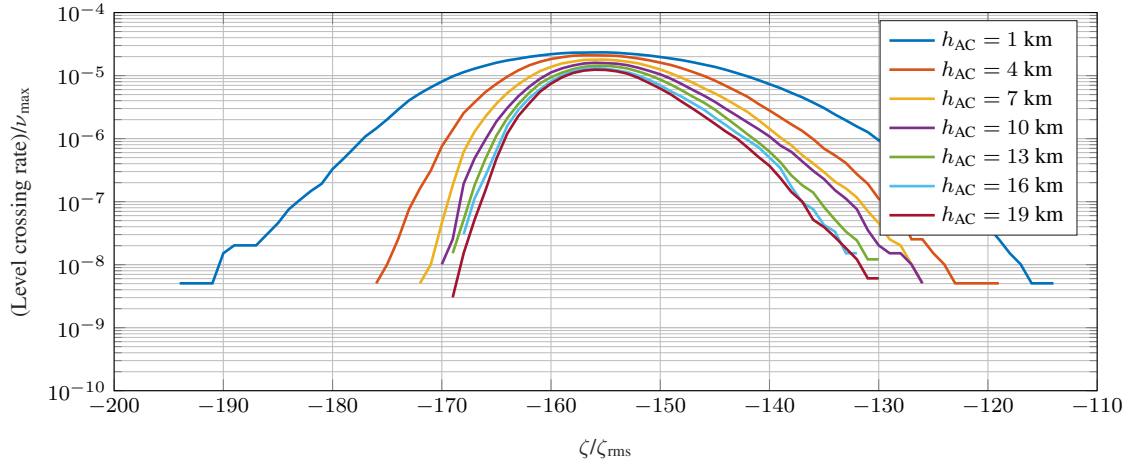


Figure 45: Level crossing rate of ζ/ζ_{rms} for different aircraft flight altitudes h_{AC} .

Key Takeaway

The aggregate FS RFI is altitude-dependent. At higher flight altitudes, as encountered in the en-route phase typical for IFE operation, the aircraft's radio horizon expands, increasing the number of visible FS stations and thus the long-term interference level. While the resulting RFI is less dynamic (lower LCR) and exhibits shorter fades (lower ADF), it remains more sustained, directly impacting continuous service quality. In contrast, lower altitudes experience higher short-term interference due to a few dominant FS stations. However, these conditions are less relevant for IFE since they occur mainly during takeoff and landing, outside the primary service phase considered in this thesis.

4 Stochastic Interference Model

With the geometric simulation requiring a considerable amount of time, which increases with flight altitude, receiver bandwidth, and FS station density, it is advantageous to employ a stochastic model for the rapid estimation of FS RFI in the aeronautical SATCOM channel. Stochastic channel models allow for efficient representation and analysis of radio communication channels by simplifying complex systems into manageable states. This section covers the transfer of the empirical data derived from the geometric simulation into the stochastic interference model, based on a finite state Markov chain (FSMC).

4.1 Finite State Markov Channel Model

Channel models based on FSMCs are widely used for the stochastic representation of radio communication channels [78]. These models capture the essential dynamics of channel states without the prohibitive computational overhead associated with extensive geometric simulations. By partitioning training data into discrete intervals that represent states of the Markov process, FSMCs effectively model state transitions and enable quick adaptations to changing channel conditions.

In an FSMC the training data is divided into a finite number of intervals, each corresponding to a state of the Markov process. Let $S = \{s_0, s_1, \dots, s_{K-1}\}$ represent a finite set of a total of K states. The sequence $\{S_n\}, n = 0, 1, 2, \dots, N_S$, is a random sequence of N_S states where each S_n represents the state at time n . This sequence satisfies the Markov property, meaning the future state depends only on the most recent state, which can be expressed as:

$$\Pr\{S_n | S_{n-1}, S_{n-2}, \dots, S_0\} = \Pr\{S_n | S_{n-1}\}. \quad (4.1)$$

The probability of transitioning from state s_x to state s_y is captured in the transition probability matrix $\mathbf{T} \in \mathbb{R}^{K \times K}$. Each element of $\mathbf{T}$ is defined as

$$t_{x,y} = \Pr(S_{n+1} = s_y | S_n = s_x) \quad (4.2)$$

where $n = 0, 1, 2, \dots, N_S$ and $x, y \in \{0, 1, 2, \dots, K-1\}$. The steady-state probability vector $\boldsymbol{\pi} = [\pi_0, \pi_1, \dots, \pi_{K-1}]$ describes the long-term behavior of the Markov chain. Specifically, π_y gives the probability of finding the system in state s_y after an infinite number of transitions, regardless of the initial state distribution, provided the FSMC is irreducible and aperiodic.

A simplified scheme of a Markov process comprising four states ($K = 4$) and the transition probabilities between the particular states is shown in Fig. 46.

The total number of states K in a model and the corresponding channel states s_k , representing in this case the states of the FS RFI ζ , significantly impact the accuracy of the

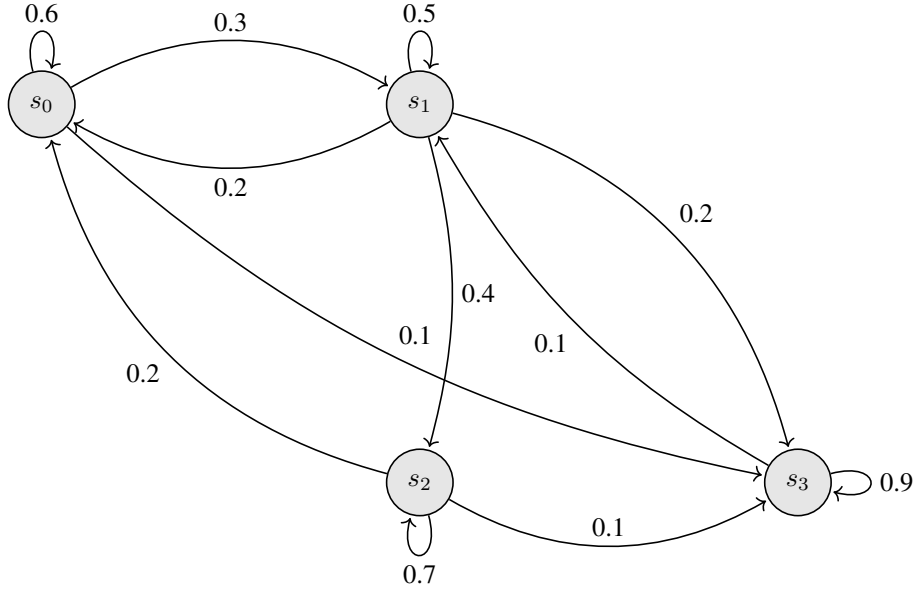


Figure 46: State diagram of an exemplary discrete-time Markov process with four states. Directed edges denote possible state transitions and are labeled with the corresponding transition probabilities, while self-loops indicate the probability of remaining in the same state.

FSMC. Determining the optimal number of states and partitioning the training data into intervals is crucial for balancing model accuracy and complexity. The goal is to provide a stochastic model with high accuracy, reasonable complexity, and computation time. To enhance the FSMC's accuracy, a higher order Markov process (HOMP) can be employed. A HOMP of order O tracks interference levels over a longer history, improving accuracy compared to a first-order Markov chain. A HOMP of order O over S states is equivalent to a first-order Markov chain over S^O states, allowing for a reduction in the total number of states and thereby decreasing complexity.

Furthermore, the time series of the simulated FS RFI exhibits the shape of the dominant FS station antenna pattern (c.f. Fig. (31)). Hence, a dependency on the previous state is given. In a HOMP, the state probability depends on the previous O states:

$$\Pr\{S_n | S_{n-1}, S_{n-2}, \dots, S_0\} = \Pr\{S_n | S_{n-1}, \dots, S_{n-O}\} \quad (4.3)$$

However, the final model accuracy and complexity depend heavily on the chosen training data partitioning scheme. Striking the right balance between these factors ensures a practical and efficient FSMC implementation.

4.2 Fading Partitioning

Partitioning schemes play a critical role in defining the states of an FSMC model, as the choice of partitioning strategy significantly impacts both the model’s accuracy and complexity. Various partitioning methods have been explored in the literature, each with distinct advantages and trade-offs [79]. Prominent examples include partitioning based on equal time duration, equal steady-state probabilities, and data-driven approaches such as clustering. The VQ method is a sound methodology to partition data for higher dimensions, e.g., for an HOMP. It is a well-known process that has recently gotten increased attention in machine learning.

Clustering is a fundamental technique in unsupervised learning. It aims to group data points such that those within the same group are more similar than those in other groups. Over the years, numerous clustering algorithms have been developed, each optimized for different types of data structures, noise characteristics, and computational constraints. Choosing the most appropriate method depends strongly on the application’s context and the data’s properties.

***K*-means** is one of the most well-known approaches. It is a centroid-based algorithm that partitions the dataset into a predefined number of clusters by minimizing the within-cluster variance [80, 81]. Due to its simplicity, scalability, and efficiency, *K*-means has become a standard method in many engineering and scientific domains. An important extension is the *X*-means algorithm, which enhances *K*-means by dynamically estimating the optimal number of clusters through a model selection criterion. This is especially useful in settings where the number of distinct groups is unknown *a priori*, as in real-world data.

Gaussian Mixture Models (GMMs) represent a probabilistic alternative, where each cluster is modeled as a Gaussian distribution. This allows for soft cluster assignments, meaning each data point has a probability of belonging to each cluster. GMMs are more flexible in modeling clusters of different shapes and sizes, especially when clusters overlap or are non-spherical [82, 81]. However, this flexibility comes at the cost of increased computational complexity and sensitivity to initialization. Moreover, the Expectation-Maximization algorithm used to train GMMs may converge to local optima, and the model selection process (e.g., choosing the number of components) is non-trivial.

Density-based methods such as DBSCAN identify clusters as regions of high data density separated by low-density boundaries. These algorithms are powerful when clusters are arbitrarily shaped or the dataset contains significant noise [83, 81]. Nonetheless, their effectiveness heavily depends on the choice of hyperparameters, such as the neighborhood

radius and the minimum number of points per cluster. Furthermore, density-based methods often struggle with high-dimensional data, where distances become less meaningful due to the curse of dimensionality.

Hierarchical clustering builds a tree of nested clusters through agglomerative or divisive approaches. This method is advantageous when the interpretability of the cluster hierarchy is important. However, it scales poorly with large datasets and does not naturally accommodate dynamic cluster estimation [84, 81].

Hidden Markov models (HMMs) are particularly suited for time-series or sequential data, as they explicitly model state transitions over time. HMMs can capture complex temporal dependencies, making them powerful tools in speech recognition, bioinformatics, and mobility modeling. Unlike clustering methods, hidden Markov models (HMMs) are not primarily designed to group static data points based on similarity. Instead, they are probabilistic models for sequential data in which the system is assumed to follow a Markov process with unobserved (hidden) states. The observed data are generated from these hidden states via an emission process, allowing HMMs to capture both the observations' temporal dynamics and statistical distribution.

An HMM can be particularly useful in extending FSMC-based channel representations to account for fast fading below the noise floor, where the actual channel state cannot be directly observed. In this context, the hidden states would represent the true fading conditions, while the noisy signal measurements (e.g., received power, SNR, interference level) would form the observation sequence.

Given the data characteristics used in this work and the need for computational efficiency and interpretability, X -means offers a well-balanced solution. It retains the simplicity and speed of K -means while eliminating the need to predefine the number of clusters. Although more sophisticated algorithms like GMMs or density-based methods may offer marginal gains in flexibility, their added complexity and parameter sensitivity are unjustified. Therefore, X -means is considered the most suitable approach for the clustering task.

Key Takeaway

Among the available clustering algorithms, the X -means method was selected for its balance between simplicity, computational efficiency, and adaptive cluster estimation. Its ability to infer the optimal number of clusters *a priori* makes it especially suitable for high-dimensional, static feature data, as found in the FS RFI modeling task. While more complex methods such as GMMs or density-based algorithms may offer increased flexibility, their added complexity and sensitivity to hyperparameters are not justified in this context.

4.2.1 K -means

K -means partitions a set of data $\mathcal{D}$ into a pre-defined, fixed number of K clusters described by their cluster centers $\mu_c \in \mathbb{R}^O$. Each cluster consists of a subset of data points assigned based on proximity to the cluster center. This assignment of the point to a cluster c is denoted by z with $z_i \in 1 \dots K$. The decision on whether a data point $\mathbf{x}_i \in \mathbb{R}^O$ is assigned to a cluster is determined by the smallest distance of the data point $\mathbf{x}_i \in \mathcal{D}$ to the adjacent cluster centers μ_c

$$z_i = \arg \min_c \|\mathbf{x}_i - \mu_c\|^2 \quad \forall \mathbf{x}_i \in \mathcal{D}, \quad (4.4)$$

where $\|\cdot\|^2$ is the squared Euclidean norm, or L2-norm. After assigning all data points to clusters, the cluster centers are updated to be the average of all data points assigned to the respective cluster.

$$\mu_c = \frac{1}{R_c} \sum_{i \in S_c} \mathbf{x}_i \quad \forall c \quad (4.5)$$

Where S_c is the set of data points whose assignments z are equal to c , $S_c = \{i : z_i = c\}$ and R_c is the total number of the data points in the set assigned to cluster c . These steps, assignment of data points and update of cluster centers are then repeated until the cluster centers converge. The K -means clustering algorithm optimizes a cost function by assigning data points from the training sequence to the cluster centers with respect to their squared Euclidean norm. The number and definition of the cluster centers determine the accuracy and complexity of the model, which can be quantified by a cost function C

$$C(\underline{z}, \underline{\mu}) = \sum_i \|\mathbf{x}_i - \mu_{z_i}\|^2. \quad (4.6)$$

Here, μ_{z_i} is the cluster center assigned via z_i . The optimal number of clusters K_o in K -means would theoretically minimize this cost function, e.g., assigning each data point to its own cluster. In practice, selecting an arbitrary number of clusters K may lead to

suboptimal accuracy and complexity in representing the underlying data distribution. No real optimization of the channel states regarding accuracy and complexity can be obtained by arbitrarily choosing a random number cluster centers.

In the context of stochastic processes, the selection of the number and definition of clusters impacts the accuracy and complexity of the model. For example, in a HOMP with order $O = 2$, a single state $\mathbf{s}_k = [\zeta_l, \zeta_{l+1}]^\top \in \mathbb{R}^2$ represents the transition from ζ_l to ζ_{l+1} , where $[\cdot]^\top$ denotes the transpose operation. As O increases, the complexity of the transition probability matrix $\mathbf{T}$ grows. To address this issue, the X -means clustering algorithm is used. Unlike K -means, which requires the number of clusters, K , to be specified a priori, X -means achieves this by iteratively refining the number of clusters through a process guided by the Bayesian Information Criterion (BIC) [85]. By automatically determining the optimal number of clusters it is ensured that the number of channel states is optimized for a reduced and manageable transition probability matrix $\mathbf{T}$.

4.2.2 X -means

Proposed by Pelleg et al. [86], the X -means algorithm enhances the traditional K -means algorithm to estimate the optimal number of clusters K_o through the optimization of a cost function related to data assignments and cluster centers. This cost function is evaluated using the squared Euclidean norm and a criterion that accounts for model complexity. In X -means, the BIC or Schwarz Information Criterion [85] is used to decide whether the chosen model $\mathcal{M}$ with a certain number of clusters is optimal. The BIC measures the statistical data's goodness of fit by introducing a penalty term for the number of parameters in the model, which helps prevent overfitting.

The X -means algorithm begins with a predefined number of clusters $1 < K < K_{\max}$, performing the K -means algorithm over K clusters using the data set $\mathcal{D}$ until convergence is reached. Afterward, half of the clusters (specifically $K/2$) are chosen arbitrarily and divided into two subsets. The new model $\mathcal{M}_{q+1}$ out of Q models has therefore $K_{q+1} = \lfloor 1.5K_q \rfloor$ clusters, with $\lfloor \cdot \rfloor$ denoting the floor operation. The K -means algorithm is then executed on the new cluster centers until convergence is achieved once more.

Following convergence by K -means, the BIC values for both the new and previous models are compared, with the model exhibiting the higher BIC value being selected. This process continues until either no higher BIC value can be achieved, determining K_o , or the predefined maximum cluster value $K_{\max}$ is reached. The process of applying the X -means algorithm for clustering of the training data $\mathcal{D}$ is depicted in Fig. 47 using the formulas of the previous sections as well as the ones being derived in the following sections with respect to the BIC.

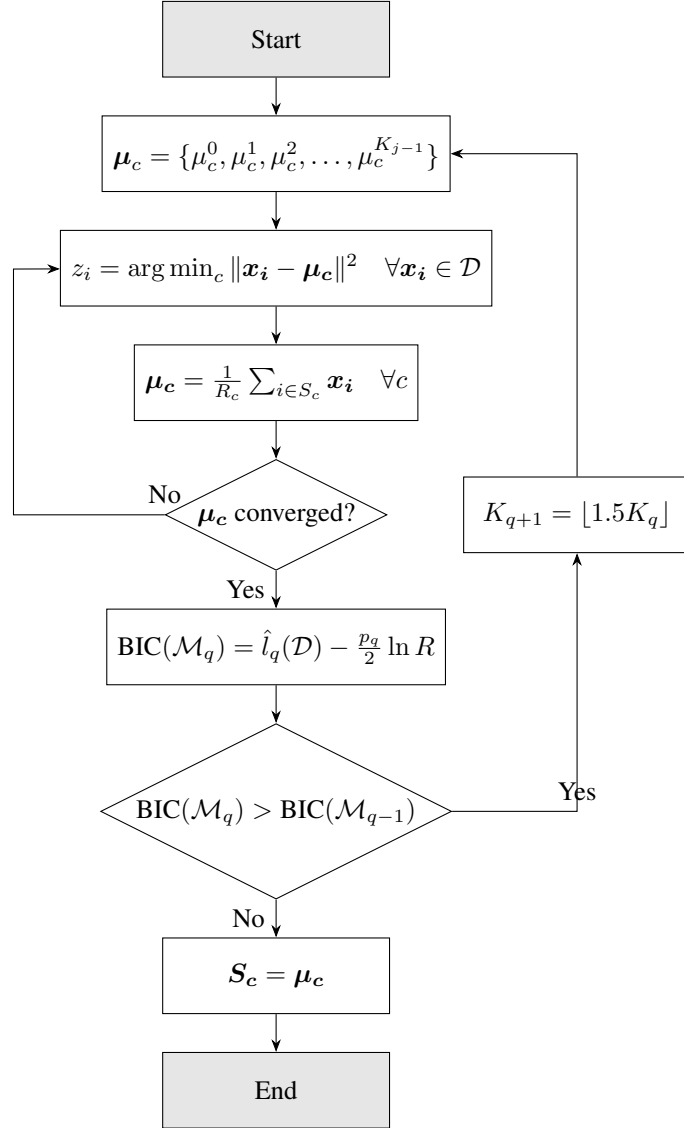


Figure 47: Flowchart of the X -means algorithm as applied to derive optimal cluster centers for the state partitioning of the finite-state Markov process.

The BIC for the q th model is computed as follows [86]:

$$\text{BIC}(\mathcal{M}_q) = \hat{l}_q(\mathcal{D}) - \frac{p_q}{2} \ln R \quad (4.7)$$

$\hat{l}_q(\mathcal{D})$ represents the maximum log-likelihood estimate of the data $\mathcal{D}$ under the model $\mathcal{M}_q$ evaluated at the model's maximum-likelihood point. The term p_q represents the number of free parameters in the model $\mathcal{M}_q$. The variable R refers to the number of data points in $\mathcal{D}$, corresponding to the number of simulation samples.

To model multidimensional data, the distribution of points is approximated by a multivariate Gaussian distribution. The log-likelihood estimate of independent dataset $\mathcal{D}$ under the model $\mathcal{M}_q$ is given by

$$l_q(\mathcal{D}) = \ln \prod_{\mathbf{x}_i \in \mathcal{D}} p(\mathbf{x}_i) = \sum_{\mathbf{x}_i \in \mathcal{D}} \ln p(\mathbf{x}_i) \quad (4.8)$$

where $p(\mathbf{x}_i)$ denotes the probability density of a data point $\mathbf{x}_i$. In a model-based clustering approach with K Gaussian components, this probability is given by

$$p(\mathbf{x}_i) = \sum_c c = 1^K p(\mathbf{x}_i \in S_c) \cdot p(\mathbf{x}_i | \mathbf{x}_i \in S_c), \quad (4.9)$$

where $p(\mathbf{x}_i \in S_c)$ is the prior probability of component c , and $p(\mathbf{x}_i | \mathbf{x}_i \in S_c)$ is the component-specific multivariate Gaussian likelihood. $p(\mathbf{x}_i \in S_c) = R_c/R$ is the probability that $\mathbf{x}_i$ belongs to the set of data points to the n th cluster S_c , proportional to the number of points R_c in that cluster.

$p(\mathbf{x}_i | \mathbf{x}_i \in S_c)$ denotes the Multivariate Gaussian density centered at μ_c . In the generic multivariate Gaussian distribution, each cluster can have its own covariance matrix Σ_c , leading to

$$p(\mathbf{x}_i | \mathbf{x}_i \in S_c) = \frac{1}{(2\pi)^{O/2} |\Sigma_c|^{1/2}} \exp \left(-\frac{1}{2} (\mathbf{x}_i - \mu_c)^\top \Sigma_c^{-1} (\mathbf{x}_i - \mu_c) \right). \quad (4.10)$$

O denotes the dimension of the multivariate Gaussian distribution, which is the HOMP order $O = 2$ in the considered case. In the X -means approach proposed by Pelleg et al., a multivariate Gaussian distribution assuming an identical spherical assumption is applied. By assuming all clusters have the same covariance matrix, which is diagonal and isotropic, the Gaussian density for a set of data in the a cluster S_c can be simplified to

$$P(\mathbf{x}_i | \mathbf{x}_i \in S_c) = \frac{1}{(2\pi\sigma_c^2)^{O/2}} \exp \left(-\frac{\|\mathbf{x}_i - \mu_c\|^2}{2\sigma_c^2} \right). \quad (4.11)$$

σ_c^2 denotes the variance of the distribution of the set of data in the particular cluster S_c . The identical spherical assumption limits the accuracy as the data would exhibit clusters with other shapes or differing variances, which the spherical assumption cannot capture. On the other hand, handling arbitrary covariance matrices for each cluster introduces significant computational overhead. The simplified model reduces the number of parameters and makes the algorithm efficient. With isotropic clusters, the behavior of the clustering algorithm becomes more intuitive. Clusters are modeled as circles or spheres around their centroids, depending on the order of the HOMP.

This assumption made by Pelleg et al. requires some additional considerations to determine the maximum log-likelihood estimate. The simplified Gaussian density in (4.11) is substituted in (4.8) to calculate the log-likelihood estimate for the BIC

$$l_q(\mathcal{D}) = \sum_{x_i \in \mathcal{D}} \left[\ln \frac{R_c}{R} - \frac{O}{2} \ln (2\pi\sigma^2) - \frac{\|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2}{2\sigma^2} \right]. \quad (4.12)$$

Instead of summing over all data points individually, the sum is reorganized to group terms belonging to each cluster. Each data point $\mathbf{x}_i$ belongs to exactly one cluster c , so the sum over i into K can be split in separate sums, one for each cluster:

$$l_q(\mathcal{D}) = \sum_{c=1}^K \sum_{x_i \in S_c} \left[\ln \frac{R_c}{R} - \frac{O}{2} \ln (2\pi\sigma_c^2) - \frac{\|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2}{2\sigma_c^2} \right] \quad (4.13)$$

The term R_c/R depends only on the cluster size R_c and is constant for all points in the same cluster. When summed over all points in S_c (4.13) simplifies to

$$\sum_{x_i \in S_c} \ln \frac{R_c}{R} = R_c \ln \frac{R_c}{R}. \quad (4.14)$$

The term $-O/2 \cdot \ln(2\pi\sigma_c^2)$ is also constant for all points in S_c , hence

$$\sum_{x_i \in S_c} \left(-\frac{O}{2} \ln (2\pi\sigma_c^2) \right) = R_c \left(-\frac{O}{2} \ln (2\pi\sigma_c^2) \right). \quad (4.15)$$

The last term in (4.13) depends on the individual points in S_c and can be restructured to

$$\sum_{x_i \in S_c} -\frac{\|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2}{2\sigma_c^2} = -\frac{1}{2\sigma_c^2} \sum_{x_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2. \quad (4.16)$$

Putting (4.14), (4.15) and (4.16) into (4.13) provides the simplified term of the log-likelihood for each cluster

$$l_q(\mathcal{D}) = \sum_{c=1}^K \left[R_c \left(\ln \frac{R_c}{R} - \frac{O}{2} \ln (2\pi\sigma_c^2) \right) - \frac{1}{2\sigma_c^2} \sum_{x_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2 \right]. \quad (4.17)$$

The maximum likelihood estimate for the variance $\hat{\sigma}_n^2$ is determined by setting the derivative of the log-likelihood to zero.

$$\begin{aligned}
\frac{\partial l_q(\mathcal{D})}{\partial \sigma} &= \sum_{c=1}^K \left[-\frac{OR_c}{\sigma_c} + \frac{1}{\sigma_c^3} \sum_{\mathbf{x}_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2 \right] \\
&= \sigma^{-3} \sum_{c=1}^K \left[-OR_c \sigma_c^2 + \sum_{\mathbf{x}_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2 \right] \\
&= \sigma^{-3} \left[-OR\sigma^2 + \sum_{\mathbf{x}_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2 \right],
\end{aligned} \tag{4.18}$$

which is zero when

$$\hat{\sigma}^2 = \frac{1}{OR} \sum_{\mathbf{x}_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2. \tag{4.19}$$

Both estimates for the variance are proportional to the sum of the distances from each data point to the nearest centroid. This sum can be broken down into the sum by clusters,

$$\sum_{\mathbf{x}_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2 = \sum_{c=1}^K \sum_{\mathbf{x}_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2. \tag{4.20}$$

Each individual cluster is a spherical Gaussian distribution. The variance of a set of data points is defined as the average squared deviation of the points from their mean, but adjusted by the Bessel correction [87] $R_c - 1$ in the denominator to make the estimator unbiased. For a set of R_c data points $\mathbf{x}_i \in S_c$ in the c th cluster, the unbiased sample variance is calculated by:

$$\hat{\sigma}_n^2 = \frac{1}{O(R_c - 1)} \sum_{\mathbf{x}_i \in S_c} \|\mathbf{x}_i - \boldsymbol{\mu}_c\|^2. \tag{4.21}$$

Putting (4.21) into (4.20) gets

$$\sum_{\mathbf{x}_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2 = O \sum_{c=1}^K (R_c - 1) \hat{\sigma}_c^2. \tag{4.22}$$

In assuming the identical spherical assumption, where all the Gaussian distributions have the same variance, $\hat{\sigma}_c^2 = \hat{\sigma}^2$. Then (4.22) can be reformulated to

$$\begin{aligned}
\sum_{\mathbf{x}_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2 &= O \left(\sum_{c=1}^K (R_c) - \sum_{c=1}^K (1) \right) \hat{\sigma}^2 \\
&= O(R - K) \hat{\sigma}^2,
\end{aligned} \tag{4.23}$$

or, when solved for $\hat{\sigma}^2$

$$\hat{\sigma}^2 = \frac{1}{O(R-K)} \sum_{x_i \in \mathcal{D}} \|\mathbf{x}_i - \boldsymbol{\mu}_{c(i)}\|^2. \quad (4.24)$$

Using the maximum likelihood assumption from (4.17):

$$\begin{aligned} \hat{l}_q(\mathcal{D}) &= \sum_{c=1}^{K_q} \left[R_c \left(\ln \frac{R_c}{R} - \frac{O}{2} \ln(2\hat{\sigma}^2) \right) - \frac{1}{2\hat{\sigma}^2} M(R_c - 1) \hat{\sigma}^2 \right] \\ &= \sum_{c=1}^{K_q} \left[R_c \ln R_c - R_c \ln R - \frac{R_c O}{2} \ln(2\pi\hat{\sigma}^2) - \frac{1}{2} O(R_c - 1) \right], \end{aligned} \quad (4.25)$$

and $\sum_{c=1}^K R_c = R$, leads to the final formula to calculate the maximum log-likelihood estimation $\hat{l}_q(\mathcal{D})$ to be used in (4.7)

$$\hat{l}_q(\mathcal{D}) = \sum_{c=1}^{K_q} R_c \ln R_c - R \ln R - \frac{RO}{2} \ln(2\pi\hat{\sigma}^2) - \frac{O}{2}(R - K_q). \quad (4.26)$$

Finally, the number of free parameter p_q has to be determined. It is calculated to be the sum of all coordinates of the cluster centroids, one estimated variance, and the class probabilities

$$p_q = K_q - 1 + MK_q + 1 = K_q(M + 1). \quad (4.27)$$

Key Takeaway

The formulation of the X -means algorithm is mathematically derived by combining the maximum log-likelihood estimate of a simplified Gaussian model with the Bayesian Information Criterion as a model selection metric. Under the assumption of isotropic, spherical clusters, the log-likelihood and number of free parameters can be computed efficiently, enabling a systematic and computationally tractable determination of the optimal number of clusters.

4.2.3 Application of X -means

When using a HOMP, each channel state is represented as a vector $\mathbf{s}_k \in \mathbb{R}^{1 \times O}$. For the selected HOMP order, each channel state captures the transition between cluster centers and is expressed as $\mathbf{s}_k = [\mu_{c_x}, \mu_{c_y}]^\top$, and μ_{c_x} and μ_{c_y} represent the x th and y th cluster centers, respectively. When applying the X -means algorithm to the training data for $O = 2$ and for the two representative A-ESIM antenna diameters, the optimal number of cluster, respectively, the optimal number states to create a series of FS RFI ζ is $K_o = 109$ for the training sequence of $D_{AC}/\lambda < 50$ and $K_o = 163$ for $D_{AC}/\lambda \geq 50$.

The associated BIC as a function of the number of cluster centers and derived during the X -means algorithm is shown in Fig. 48. The resulting clustering of the training sequence allocating the data points to cluster centroids, which define the channel states of the FSMC, is exemplary shown for the data, derived for $D_{AC}/\lambda < 50$ in the Voronoi diagram in Fig. 49. With K_o being determined, the optimized transition probability matrix of the FSMC is determined to be of the size $\mathbf{T}_o \in \mathbb{R}^{K_o \times K_o}$, i.e.

$$\mathbf{T}_o = \begin{bmatrix} t_{1,1} & \dots & t_{1,K_o} \\ \vdots & \ddots & \vdots \\ t_{K_o,1} & \dots & t_{K_o,K_o} \end{bmatrix}. \quad (4.28)$$

The transition probabilities for each state are determined according to the definition in (4.2) and are verified to meet the property of the transition probability matrix that the sum of

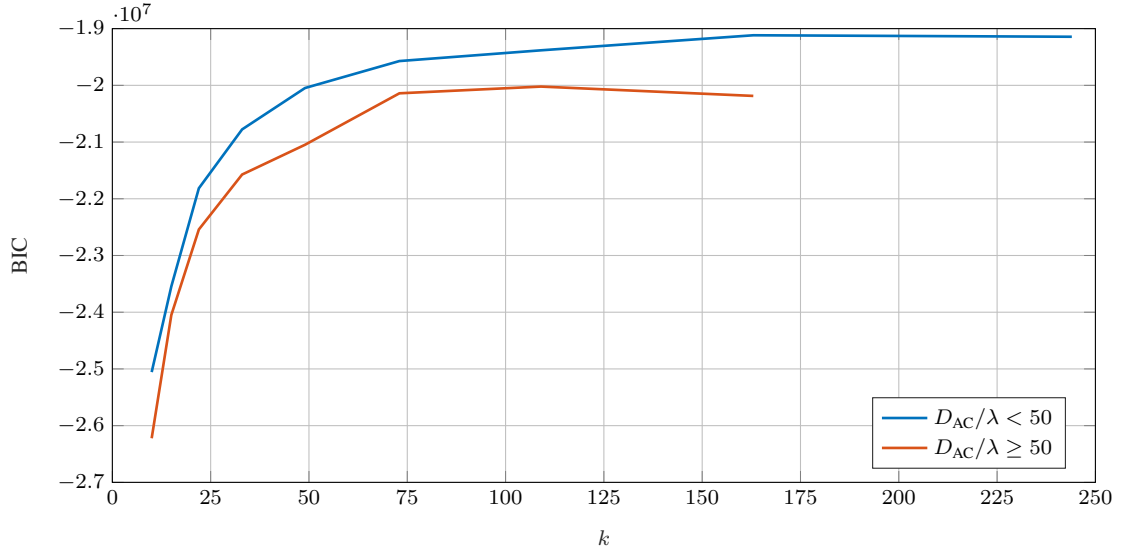


Figure 48: Bayesian Information Criterion versus the number of cluster centers k for the training data, indicating optimal values of $K_o = 109$ for $D_{AC}/\lambda < 50$ and $K_o = 163$ for $D_{AC}/\lambda \geq 50$.

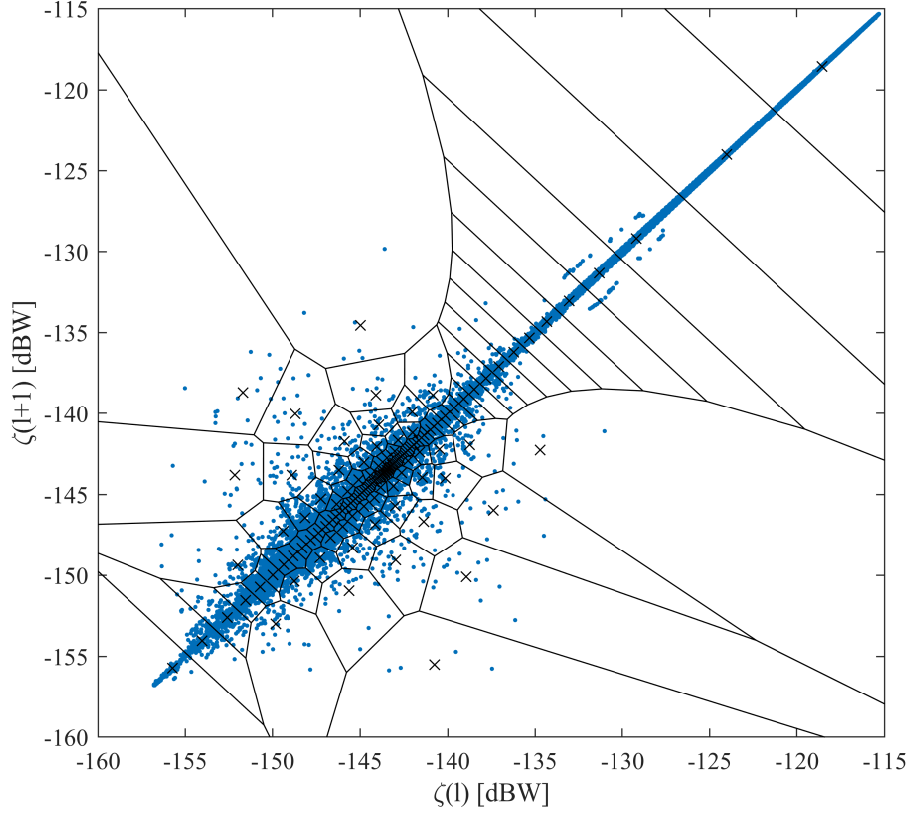


Figure 49: Voronoi diagram of the cluster center compared to the simulated transitions showing the assignments of each transition to the particular cluster center for the antenna diameter $D_{AC}/\lambda < 50$

the elements on each row is equal to 1, or, respectively,

$$\sum_{z=0}^{K_o-1} t_{x,z} = 1, \forall x \in \{0, 1, 2, \dots, K_o - 1\}. \quad (4.29)$$

The determined FSMC parameters, i.e. the channel states and the transition probability matrix for a FS RFI sequence are presented for their respective first entries of the $D_{AC}/\lambda \geq 50$ -case in (C.1) in Appendix C, for the first entries of the $D_{AC}/\lambda < 50$ -case in (D.1) in Appendix D. The values of the cluster centers are shown in (E.1) in Appendix E and (F.1) in Appendix F, for the two antenna diameters, respectively. The full FSMC parameters (transition probability matrices and cluster centers) for both antenna diameters are embedded in the electronic version of this thesis as an attachment as Microsoft Excel spreadsheets. Alternatively, the FSMC data can be downloaded under a GNU license from [88].

4.3 Results and Discussion

Following the determination of states by VQ, a time series of states using the cluster centers derived by the X -means algorithm is generated with an FSMC. For statistical comparison with the original simulation data, the same number of samples is generated as simulated in the deterministic model to allow for comparison of the derived statistics by their MSE. The generated time series of stochastic states for 250 minutes is shown in Fig. 50 for the two antenna diameters. The pdf of the series of states is then derived with the KDE method introduced in section 3.3.1 and compared with the pdf from the simulation. The MSE is used as a metric to compare both pdfs, allowing for the evaluation of the accuracy of the stochastic model. This comparison of the cdfs and their respective MSEs is presented in Fig. 51 and similarly for the cdfs in Fig. 52.

Both figures exhibit an excellent match between the predicted values using the stochastic HOMP and the simulated models. The MSE on each diagram is below 10^{-4} . However, in the pdf in Fig. 51, deviations can be observed at values of ζ having lower probabilities. They result from the applied partitioning scheme. The K -means clustering, which is the basis of X -means, optimizes a cost function assigning data points from the training sequence to the cluster centers according to their squared Euclidean norm. Hence, the number of clusters increases where more data points exist that influence the cost function more than those with less probability. This clustering characteristic of the K -means algorithm can be seen in the Voronoi diagram in Fig. 49. It leads to many clusters in regions with a high density of samples, resulting in an excellent fit of the pdf in regions of high probability. Data points that do not occur frequently, thus having a lower probability, are combined, creating larger deviations. When considering the aggregate FS RFI together with the receive noise of the aircraft, which is shown in Fig. 14 to be for the cho-

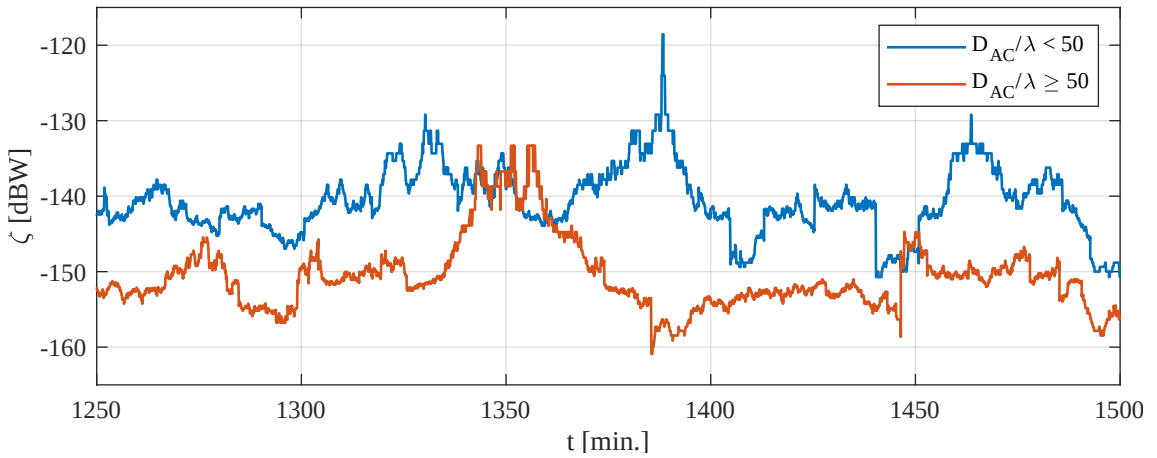


Figure 50: State time series generated by a finite state Markov chain using cluster centers obtained from the X -means algorithm, shown for an arbitrary 250-minute interval.

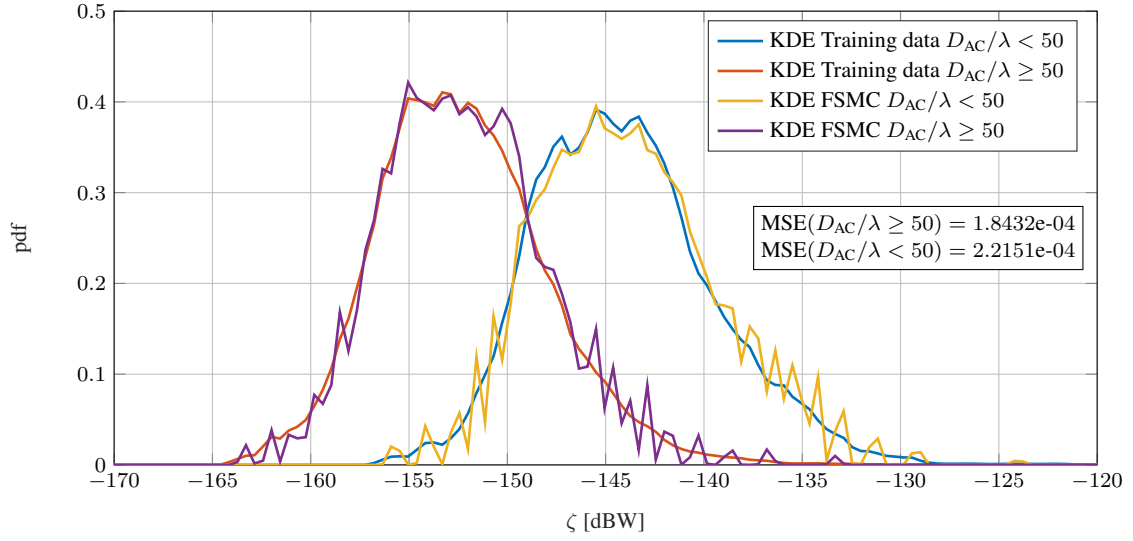


Figure 51: Probability density functions of the training sequence obtained via kernel density estimation, compared with those generated by the finite state Markov chains for $h_{AC} = 10$ km, with $D_{AC}/\lambda \geq 50$ and $D_{AC}/\lambda < 50$.

sen configuration -133 dBW for SATCOM terminals, it can be concluded that for low values of $\zeta < -140$ dBW, these deviations would not impact the accuracy of the model as those values are sufficiently below the noise. For the higher values of $\zeta \geq -140$ dBW, and which values are of greater interest, a channel state of the FS RFI covers a range of $\Delta\zeta = \pm 3$ dB. Those higher levels of ζ , being of the short term and thus most severe for the IFE link, would be modeled with less accuracy and subject to improved partitioning. For the statistical assessment, the accuracy is sufficient. An improvement of the clustering algorithm to capture these outliers is proposed in section 4.4.

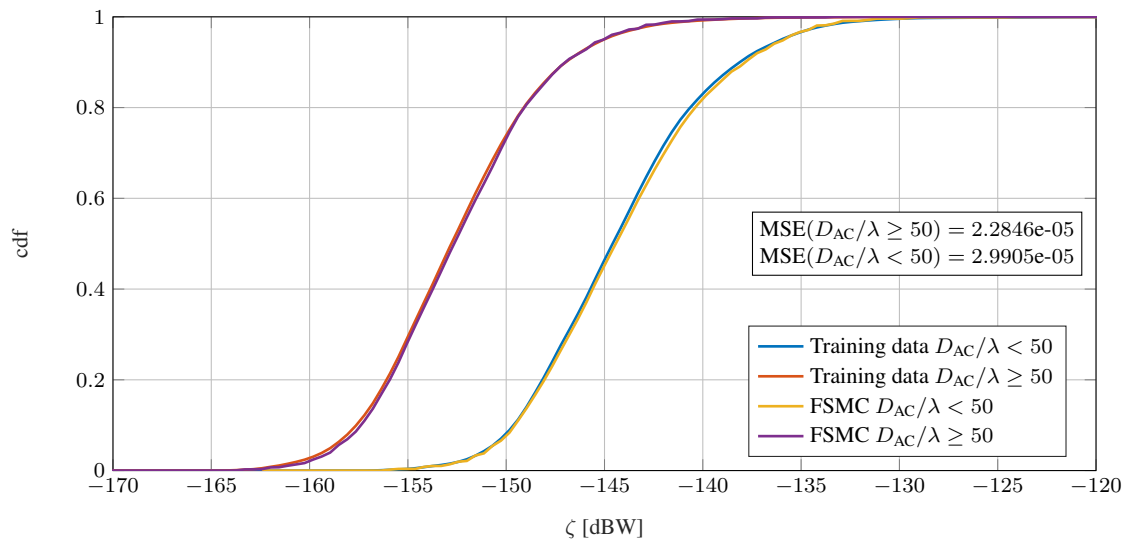


Figure 52: Cumulative distribution functions of the training sequence compared with the cumulative distribution functions of the finite state Markov chains

Regarding the flexibility of the stochastic model to be applicable for different flight velocities, the FSMC process can be adapted by scaling the time index associated with the sequence of states. The current time index is identical to the deterministic model's simulation time step, which is $\Delta t = 0.1$ s. Depending on the flight velocity, the associated time step l can be scaled to different v_{AC} using the methodology described in section 4.5.2. The pdf and cdf are applicable for all v_{AC} , the ADF and LCR in Fig. 35 and Fig. 36 could be scaled to the velocity using the respective maximum Doppler frequency shift.

Key Takeaway

A finite-state Markov chain based on X -means clustering accurately replicates the statistical behavior of simulated FS RFI time series, achieving MSE values below 10^{-4} for both antenna configurations. While the X -means algorithm has less accuracy in low-probability regions, low-interference power states are not critical for performance evaluation, as they fall below the receiver noise threshold. The model thus offers a statistically sound and scalable representation of interference dynamics, including support for varying flight velocities.

4.4 Clustering Improvements

To cope with the deviation in the stochastic model at transitions at a high levels of $\zeta(l)$ and $\zeta(l+1) > -130$ dBW, a different clustering algorithm can be used. Multiple clustering algorithms are available in the literature [89], all serving specific purposes with advantages and disadvantages. The main idea of all clustering algorithms is to find similarities and group data according to those similarities. In the case of the FS RFI modeling and partitioning of the interference states, those points are of interest, which are of high level but most often associated with a low probability. The X -means algorithm effectively performs even on large data but is not optimized for detecting outliers. An optimization of the X -means algorithm can be made to restrict the Euclidean norm to assign a point x_i to a cluster center μ_c

$$z_i = \arg \min_c \|x_i - \mu_c\|^2 \quad \forall \quad x_i = \{x_i | \|x_i - \mu_c\|^2 \leq \Delta\zeta\} \quad (4.30)$$

where $\Delta\zeta$ denotes the maximum deviation of a sample from a cluster center. In the modified algorithm, whose flow chart is shown in Fig. 53, X -means clustering is performed until the cluster centers reach convergence. After initially assigning each data point to a cluster center, all points whose L2-norm to the nearest centroid exceeds a specified

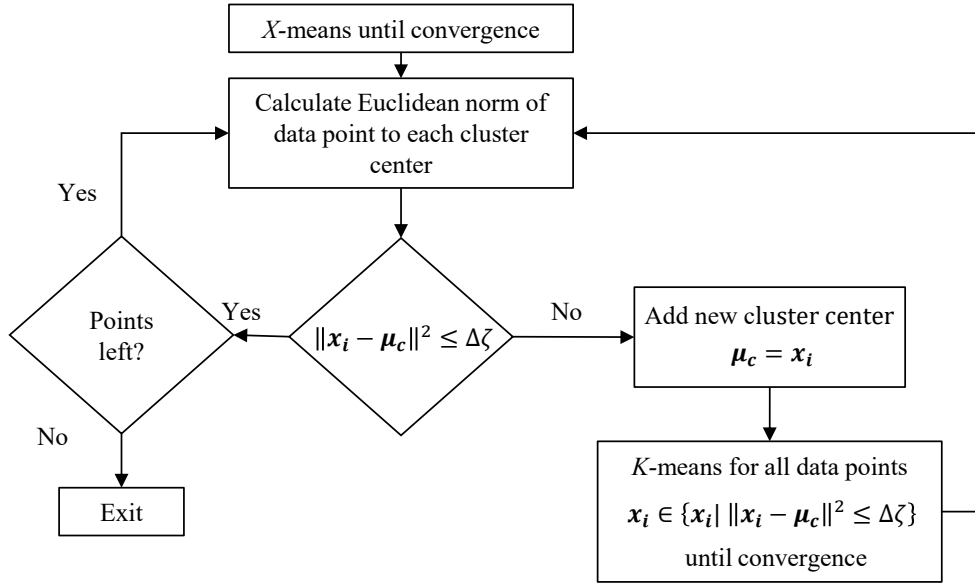


Figure 53: Flow chart of the algorithm to improve clustering

threshold $\Delta\zeta$ are identified.

A loop is then executed in which a new cluster center is added at the first point in the list exceeding this threshold, i.e., $\mu_c = x_i$. Subsequently, X -means clustering is re-applied to all data points by recalculating the L2-norm to the current centroids. The centroids are then updated, but only for those clusters whose data points satisfy the condition $x_i = \{x_i | \|x_i - \mu_c\|^2 \leq \Delta\zeta\}$. This ensures that adjacent points are reassigned to the newly added cluster center, while neighboring clusters are updated exclusively with points within the defined distance threshold. The resulting clustering assuming $\Delta\zeta = 1$ dB is shown in Fig. 54.

This algorithm is associated with an increase in complexity. The number of cluster centers for the shown particular case has increased from $K_0 = 109$ to $K = 200$, resulting in a transition probability matrix of the size $\mathbf{T} \in \mathbb{R}^{200 \times 200}$. However, the outliers are now covered precisely either directly by a cluster center or areas where the number of clusters was limited, which exhibit a higher density of cluster centers and, thus, a higher number of states. The modification allows outliers to be more accurately captured, either directly by a dedicated cluster center, or indirectly by increasing the local density of centroids in previously sparse regions, thus improving the granularity of state representation.

Applying this optimization within the FSMC framework depends on the required modeling accuracy, particularly when it is important to capture rare or extreme states. While this optimized clustering is not used in the stochastic modeling of aggregate FS RFI, where a balance between model complexity and accuracy is prioritized, it was successfully applied for the compression of three-dimensional pfd masks of non-GSO FSS systems submitted to the ITU for examination of protection of the GSO for examination

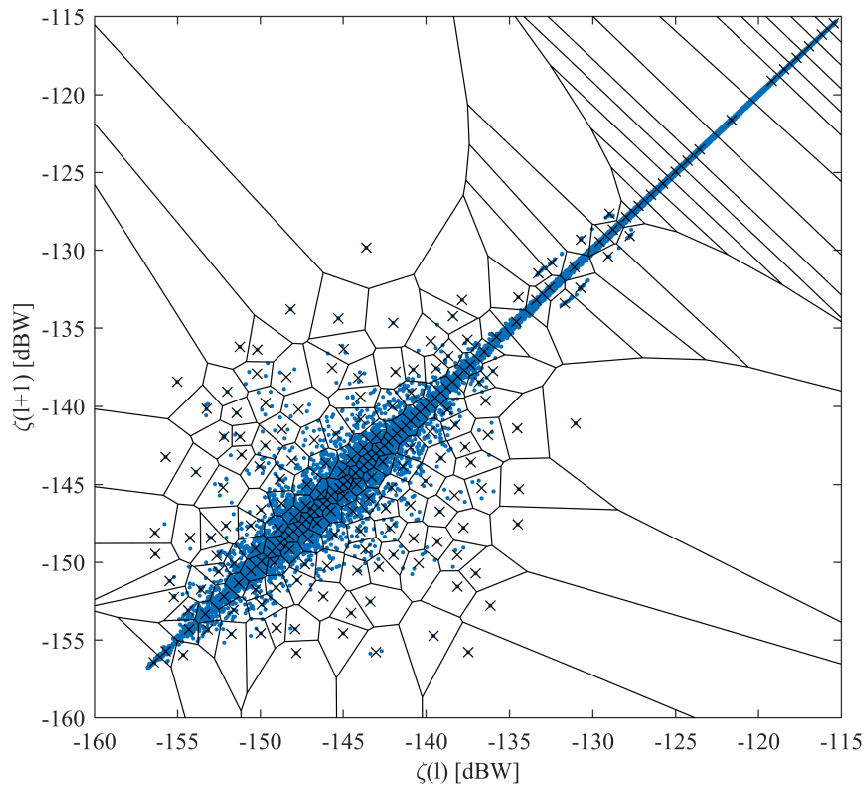


Figure 54: Voronoi diagram of the cluster centers obtained with the optimized outlier-handling algorithm, compared to the simulated transitions for $\Delta\zeta = 1$ dB, resulting in 250 cluster centers.

of equivalent power flux-density (epfd) limit. These masks ensure compliance with the protection criteria for GSO networks in the 17.8-18.6 GHz and 19.7-20.2 GHz bands, as specified in ITU-RR No. 22.5C and related provisions.

Key Takeaway

A simple extension can improve the outlier-aware clustering method. This method improves the FSMC's ability to capture high-level, low-probability FS RFI states by iteratively inserting new cluster centers beyond a predefined deviation threshold. This additional loop significantly increases model accuracy in critical regions at the cost of higher complexity. While not used for the aggregate model due to this trade-off, the method proved effective in compressing 3D pfd masks for regulatory purposes in ITU non-GSO filings, where outliers are the most important interference contributors.

4.5 Scaling of the Stochastic Model

When applying the stochastic FSMC, it is desirable to scale the model to different technical and operational characteristics of the A-ESIM. The generated data from the HOMP is scalable to changes of three significant A-ESIM parameters, without re-running the simulation. The scaling allows the model to remain valid across various system configurations, offering excellent extensions of the model and minimizing computational effort. The three parameters are the receive frequency of the SATCOM antenna within the 17.7–19.7 GHz frequency range, and the associated antenna diameter, which impact the interference power levels. The third one is A-ESIM flight velocity, which impacts the time with which the FS RFI levels are associated.

4.5.1 Aircraft Antenna Diameter and Center Frequency

The formulas provided in Rec. ITU-R S.580-6 [52] describe the antenna gain as a function of the off-axis angle ϕ for specific conditions relevant to satellite communication. Importantly, these formulas allow for a scalable modeling approach, as they depend only on the dimensionless ratio D_{AC}/λ , which encapsulates antenna size and frequency. This makes it possible to reuse simulation results across a various sets of assumptions related to those two parameters. To apply these formulas for different antenna diameters or center frequencies within the 17.7–19.7 GHz frequency range, accounting for changes in the term D_{AC}/λ is necessary. This enables straightforward scaling of the model output without re-running the full simulation, which is particularly useful for parametric studies or system-level analyses under varying hardware configurations. The formulas of Rec. ITU-R S.580-6 pattern [52] for the relevant off-axis angle cases $\phi \geq 10$ degrees are

$$G(\phi) = \begin{cases} 52 - 10 \log_{10} \left(\frac{D}{\lambda} \right) - 25 \log_{10}(\phi) & \phi_r \geq \phi < \phi_b \\ 10 - 10 \log_{10} \left(\frac{D}{\lambda} \right) & \phi_b \geq \phi < 180 \end{cases} \quad (4.31)$$

with $\phi_r = 100\lambda/D$ and $\phi_b = 10^{(42/25)}$. The gains of two different antenna diameters $G_1(\phi, D_1, f_1)$ and $G_2(\phi, D_2, f_2)$ or frequencies differ, therefore, only in the term D/λ of the respective selected antenna and frequency. Hence, the difference in the aggregate FS LOS RFI $\Delta\zeta$ for all relevant angles in both cases of (4.31) is

$$\Delta\zeta = 10 \log_{10} \left(\frac{D_2}{\lambda_2} \right) - 10 \log_{10} \left(\frac{D_1}{\lambda_1} \right). \quad (4.32)$$

Applying that the difference of two logarithms is equal to the logarithm of the quotient of their linear values, and using the relation $\lambda = c_0/f$, a correction factor can be derived to scale the stochastic FSMC results from a reference configuration to a new set of antenna and frequency parameters. The initial simulation was performed for an antenna diameter

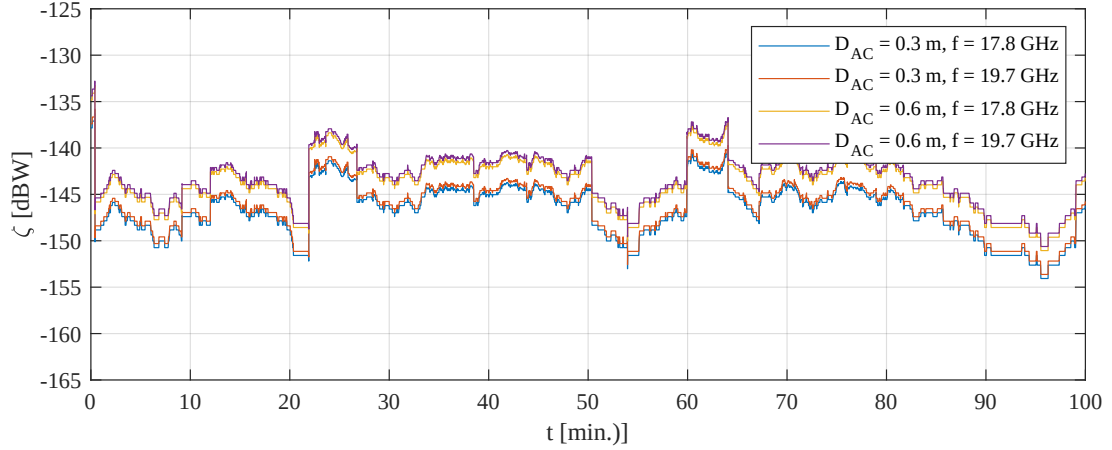


Figure 55: Time series of fixed service radio frequency interference states for 100 minutes, scaled from the original finite state Markov chain using the proposed analytical correction for different antenna sizes and frequencies, at a constant flight velocity of $v_{AC} = 500$ kts

of $D_1 = 0.3$ m and a frequency of $f_1 = 17.8$ GHz; the correction factor accounts for a new antenna diameter D_2 and / or a new center frequency f_2 . Due to the analytical structure of the antenna gain equations, the required offset can be computed directly. The resulting difference in aggregate FS LOS RFI between the two configurations can be expressed in closed form as:

$$\Delta\zeta = 10 \log_{10}(D_2 f_2) - 97.3, \quad (4.33)$$

where $\Delta\zeta$ is given in dB, D_2 in meters, and f_2 in Hertz. This correction factor serves as a simple additive offset that can be directly applied to the previously derived FSMC results. Hence, the entire interference model can be scaled to any desired antenna diameter and frequency combination within the considered band using a single algebraic transformation. Specifically, the new interference level is obtained via $\zeta_2 = \zeta_1 + \Delta\zeta$. This approach highlights the flexibility and computational efficiency of the model. The application of the correction factor for two representative antenna diameters and the edge frequencies defined in Res. 169 (WRC-23) is illustrated in Fig. 55.

In summary, the formulation enables a scalable framework for FS RFI modeling: once a representative FSMC is established for a reference case, its results can be efficiently adapted to a wide range of system configurations by applying a deterministic frequency- and antenna-dependent offset. This significantly reduces computational overhead and supports flexible system-level design evaluations.

4.5.2 Variation in Flight Velocity

In the derivation of the FSMC, a reference flight velocity of $v_{AC} = 500$ knots is assumed, using a time step of $\Delta t = 0.1$ s over $R = 5$ million samples. Applying the basic relationship between time, distance, and velocity results in a total flight distance of 1 286 611 km covered during the simulation:

$$\begin{aligned} s_{AC} &= v_{AC} \cdot R \cdot \Delta t = 500 \text{ kts} \cdot 0.514444 \frac{\text{m}}{\text{s} \cdot \text{kts}} \cdot 5e6 \cdot 0.1 \text{ s} \\ &= 1\,286\,611\,000 \text{ m}. \end{aligned} \quad (4.34)$$

The interference levels and distributions remains constant across different velocities; only the time resolution of the resulting time series must be adapted. By rearranging the distance-time-velocity relation, a new time step Δt can be calculated as

$$\Delta t = \frac{s_{AC}}{v_{AC} \cdot R} = \frac{50 \text{ s} \cdot \text{kts}}{v_{AC}} \quad (4.35)$$

with v_{AC} in nautical knots and

$$\Delta t = \frac{s}{v_{AC} \cdot R} = \frac{25.7222 \text{ m}}{v_{AC}} \quad (4.36)$$

for v_{AC} in m/s, respectively. This yields a scaling factor that ensures the same spatial path is covered, but sampled at a rate consistent with the new velocity v_{AC} . For example, at lower velocities, the same spatial sequence of interference states is traversed more slowly, leading to a longer duration per state. This approach enables the reuse of the FSMC results across different operational flight speeds, highlighting the scalability of the model with respect to aircraft dynamics.

Doppler effects resulting from changes in the flight velocity are intentionally not modeled, as the FSMC framework represents large-scale, quasi-stationary interference characteristics rather than the fast time-varying carrier-frequency shifts. Since Doppler primarily impacts the signal phase and coherence over short time scales (i.e., fast fading), which is not covered in this model, because the channel is considered as frequency flat.

The following Fig. 56 shows the stochastic time series of the FS RFI for three different flight velocities ($v_{AC_1} = 100$ kts, $v_{AC_2} = 300$ kts, and $v_{AC_3} = 500$ kts).

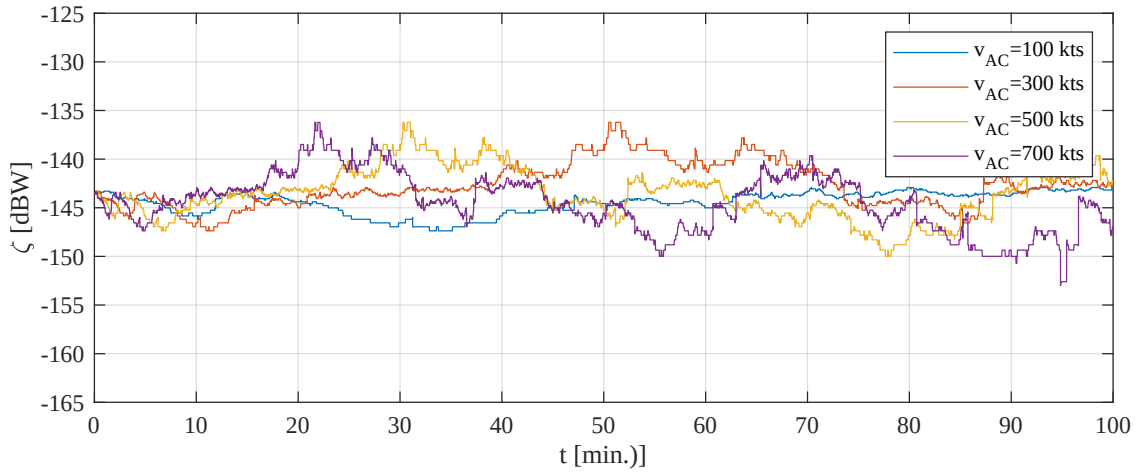


Figure 56: Time series of fixed service interference states generated by the finite state Markov chain, scaled to different aircraft velocities v_{AC} for an antenna diameter of $D_{AC} = 0.3$ m. The spatial sequence of interference states remains constant, while the temporal resolution is adjusted for each velocity.

Key Takeaway

The stochastic FSMC developed in this study exhibits a high degree of scalability of technical and operational parameters of the A-ESIM system. Applying the dependence of the FS RFI on antenna diameter, center frequency, and flight velocity, the model output can be adapted to a wide range of configurations without re-running the underlying simulation. The scaling is achieved through analytically derived correction factors that preserve the spatial and statistical properties of the interference field while adjusting the temporal or amplitude scaling.

5 Concept of an Experimental Measurement Campaign

This section presents the concept for an experimental measurement campaign to detect and characterize FS RFI in an aeronautical Ka-Band SATCOM receiver during flight. While the preceding sections focused on theoretical modeling and simulation-based quantification of interference mechanisms, this section envisions complementing the analysis with guidance for obtaining practical data from representative field measurements.

5.1 Framework of an Airborne Measurement Campaign

Conducting an airborne measurement campaign to characterize FS RFI in aeronautical SATCOM channels requires considerable logistical, technical, and financial challenges. One of the most significant hurdles is safety of flight. It requires regulatory approval to modify or equip an aircraft with specialized measurement instrumentation, especially on the outside of the aircraft. In civil aviation, any structural or electronic modification to an aircraft, especially those involving radio frequency (RF) sensors, antennas, or data acquisition units, must undergo rigorous certification procedures. These procedures, enforced by national aviation authorities (e.g., EASA in Europe or the Luftfahrt-Bundesamt in Germany [90]), ensure flight safety and electromagnetic compatibility. Consequently, obtaining the necessary approvals is time-consuming and associated with substantial costs.

In addition to regulatory hurdles, the technical integration of the measurement system into an operational aircraft demands careful planning. Not every aircraft provides the possibility of connecting outside equipment to the cabin. Thus, specific aircraft that already provide the required mounting capabilities and connections need to be modified to mount antennas and cables on the aircraft. Fig. 57 shows an exemplary aircraft in the context of a different measurement campaign having certified exterior mounting capabilities for a different electronic equipment.

An airborne measurement campaign is a resource-intensive endeavor, requiring a precise specification of measurement objectives, technical requirements, and operational constraints to ensure feasibility and scientific return. The goal of a measurement campaign is twofold. First, it should aim to detect interference experienced by a representative measurement system. This includes the identification of interference levels and their temporal and spectral variations. The measurements can confirm the derived results by capturing these effects, supporting the practical significance of the FS RFI studied in simulation.

Second, the measured data can compare empirical results directly with simulation-based predictions, enabling the validation of the modeling assumptions, system parameters, and interference propagation characteristics used throughout this work. It could



Figure 57: Assembly of external measurement equipment on a Cessa 172 wing structure.

furthermore provide added value in the information on wideband channel characteristics of the aeronautical mobile channel in the Ka-band, such as coherence time, power delay profile, or Doppler spectrum. In this context, the measurements act as an important feedback mechanism to support the credibility of the results.

Key Takeaway

An airborne measurement campaign is a complex undertaking. Aviation safety regulations and rigorous certification procedures complicate the timeline and increase associated costs when preparing the experimental campaign. Thus, the campaign and equipment must be well prepared, and longer timelines need to be considered in the schedule.

5.2 Measurement Setup

The measurement setup is designed to detect and analyze FS RFI in the Ka-band as it would be received by a nominal A-ESIM terminal. The proposed configuration, illustrated in Fig.58, consists of an antenna optimized for the 17.7-19.7 GHz frequency range. The antenna is connected to an LNB downconverter, which translates the received K- and Ka-band signals to an intermediate frequency (IF) in the L-band, suitable for digital signal processing. A software defined radio (SDR) is used to sample the full complex baseband signal, capturing both in-phase (I) and quadrature (Q) components. These samples are continuously recorded throughout the flight using a compact onboard computer, such as a

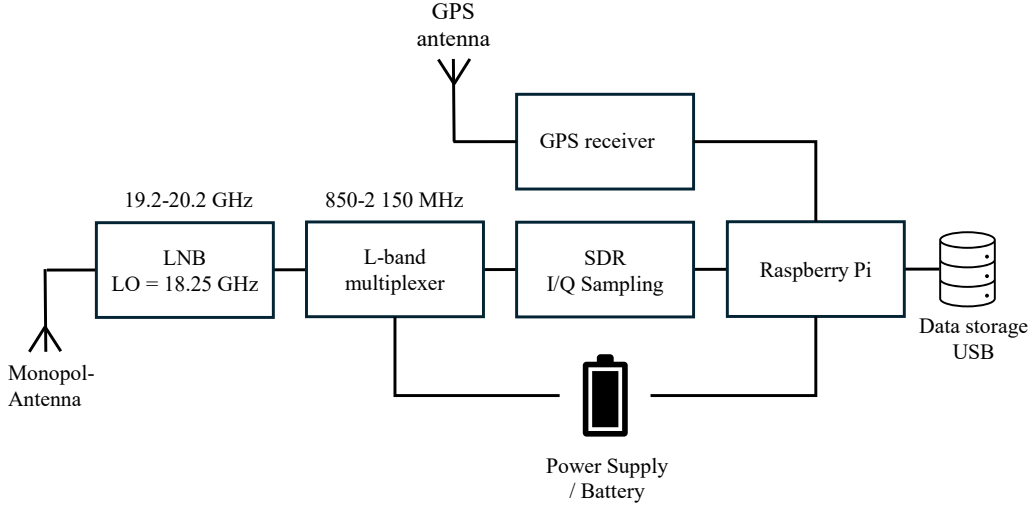


Figure 58: Block diagram of the measurement setup to detect the fixed service interference during a measurement flight

Raspberry Pi, which is particularly suitable in environments with limited space or power availability. A realization of the proposed measurement setup excluding the monopole antenna is shown in Fig. 59.

5.2.1 Antenna and Low Noise Block Converter

Due to the aircraft's restricted space and aviation security regulations for installing equipment outside of the aircraft, most probably no parabolic SATCOM antenna could be used for a measurement campaign. For that purpose, a monopole antenna optimized for the center receive frequency can be used, which is mounted in front of the LNB.

The vertically mounted monopole features a gain pattern that differs from the standard antenna pattern defined in Rec. ITU-R S.580. Unlike the directive pattern, the monopole has a more omnidirectional gain pattern. The antenna pattern of a quarter-wavelength was modeled using the Antenna Toolbox in MATLAB R2024b to quantify its radiation characteristics. The 2D elevation cuts and 3D far-field radiation patterns at a center frequency of 18.195 GHz are presented in the following Figs. 60 and 61.

In the far-field, the combined radiation from the monopole and its image yields the same field distribution as a center-fed half-wave dipole in free space [91] and is known to exhibit a theoretical maximum gain of approximately $G_{\text{di}} = 10 \log_{10}(1.643) = 2.15$ dBi. When the same current distribution is considered for the monopole over a perfect ground plane, the radiation is restricted to the upper hemisphere, effectively doubling the radiated power. As a result, the gain increases by approximately 3 dB relative to the dipole, yielding a theoretical maximum gain of:

$$G_{\text{max}} = G_{\text{di}} + 3 \text{ dB} \approx 2.15 \text{ dBi} + 3 \text{ dB} = 5.15 \text{ dBi} \quad (5.1)$$

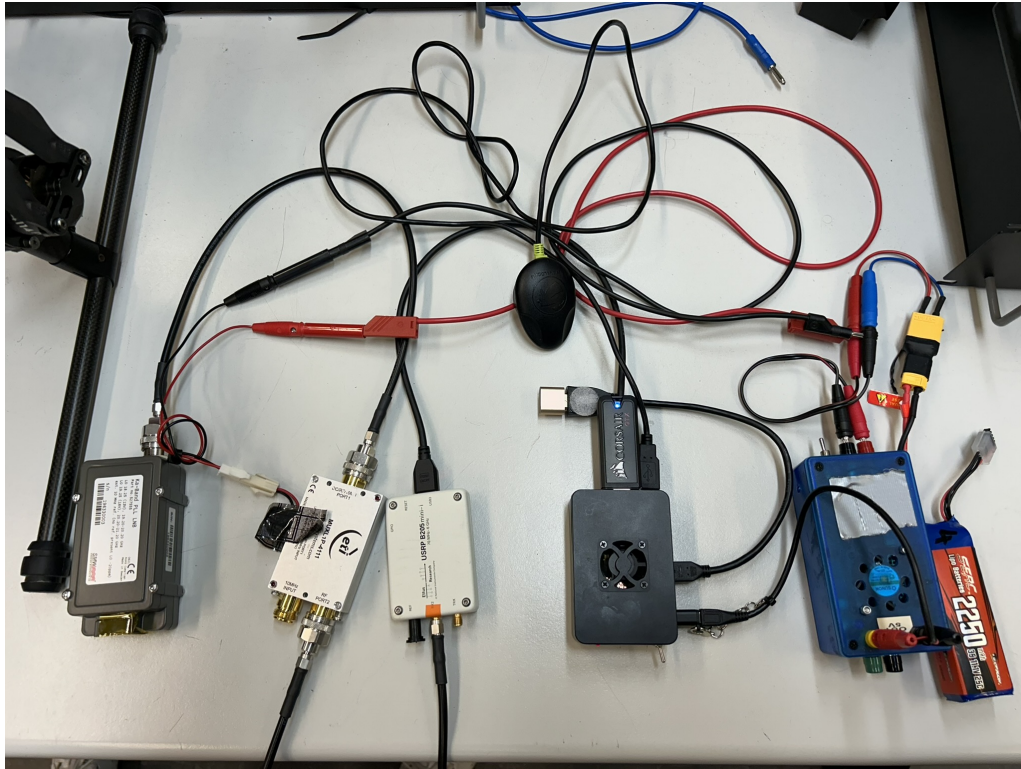


Figure 59: Implementation of the measurement setup used to capture fixed service interference during the flight test. Visible components include from left to right the low-noise block downconverter, L-band multiplexer, the software defined radio, a receiver for global positioning system signals, a Raspberry Pi, and a battery pack, corresponding to the block diagram shown in Fig.58.

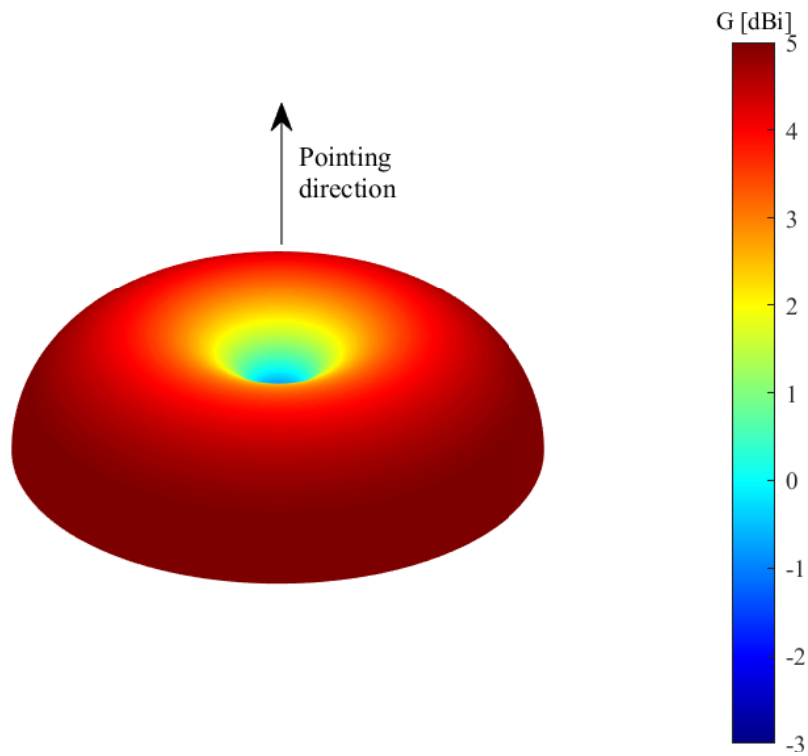


Figure 60: Simulated 3D radiation pattern of a $\lambda/4$ monopole antenna over a perfect ground plane, generated using MATLAB R2024b Antenna Toolbox

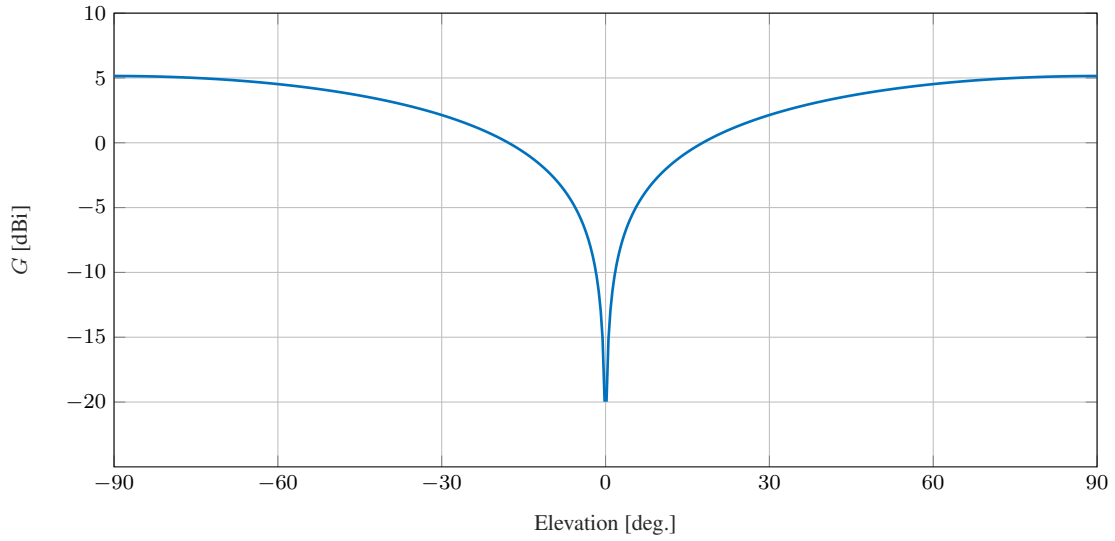


Figure 61: Elevation cut of the radiation pattern of a $\lambda/4$ monopole antenna over a perfect ground plane, simulated with MATLAB R2024b Antenna Toolbox. The pattern shows a maximum at 90 degrees, corresponding to the horizontal direction, and deep nulls at 0 degrees.

Thus the antenna gain is actually higher than the considered backlobe gain of a Rec. ITU-R S.580 or any other directional antenna pattern ($G(\varphi > 48^\circ)$) and would have to be accounted for in the post processing of the measurement data.

In the context of the measurement setup, the monopole should be mounted vertically and facing downward from the aircraft, making the antenna sensitive to signals arriving from low elevation angles, i.e., near the horizontal plane relative to the aircraft body, where according to the analysis performed in section 2.4.1, in particular Fig. 15, the highest interference events occur.

The downconversion of the high-frequency K- and Ka-band signals to an IF done by the LNB shall be supported by an additional filter or multiplexer. Available commercial of the shelf (COTS) LNBs mainly cover parts of the band.

To ensure the reliability of the measurement results, a careful calibration of the entire receiving system is required. First, the noise performance of the measurement setup must be calibrated under controlled conditions to confirm its nominal noise figure and gain stability across the operational frequency range. In the absence of a dedicated calibration signal, absolute power calibration of the received data must rely on an external reference measurement or assumptions about the thermal noise floor. One common approach is to use the known characteristics of thermal noise in a matched receiver bandwidth. The thermal noise power p_N at the input of the receiver can be estimated and can be used to calibrate the measured power p_{rx} obtained from the digital samples of the baseband signal. Assuming the receiver captures only noise during a selected silent segment of the recording, the offset between the measured digital power and the expected thermal noise

power yields a calibration constant K_{cal} in decibels:

$$K_{\text{cal}} = 10 \log_{10}(p_{\text{N}}) - 10 \log_{10}(p_{\text{rx}}). \quad (5.2)$$

This constant is applied to the entire measurement to express all received powers in absolute units. This approach assumes the receiver operates linearly and that the gain and quantization characteristics remain constant throughout the measurement. Where no noise-only segment is available, the calibration must instead rely on laboratory measurements or prior characterizations of the receiver chain.

In addition, particular attention must be paid to the antenna radiation pattern. While the antenna pattern may be well characterized in an ideal environment, the installation on an aircraft can introduce distortions due to the airframe, mounting structures, and mutual coupling with surrounding elements. Therefore, it is necessary to characterize or validate the effective antenna pattern in the installed configuration, ideally using electromagnetic simulation and/or a calibration phase on-site before flight.

5.2.2 Data Sampling

For capturing the downconverted IF signals during flight, using a SDR platform such as the Ettus Research USRP B205 Mini is optimal. This device supports complex baseband sampling with a rate of 10 MSps, corresponding to a time resolution of 100 ns per sample, which is sufficient to capture the temporal dynamics of interference signals in the fixed service band. Complete complex I and Q samples should be recorded continuously throughout the flight to ensure an unfiltered and complete representation of the received signal environment.

The choice of the bandwidth is a trade-off between fidelity to the simulated interference scenarios and the practical constraints of data acquisition and storage. While the interference simulation model assumes a 20 MHz bandwidth, capturing 20 MHz in-flight at high sampling rates leads to substantial data volumes, which can strain storage and processing capabilities, especially for long-duration flights. In practical implementations, reducing the measurement bandwidth to a representative sub-band centered within the simulation band can be considered. This allows sufficiently high time resolution and spectral fidelity to characterize interference behavior while significantly reducing data rates. Ultimately, the selected bandwidth should balance realism, resource constraints, and the specific goals of the measurement campaign. The analog IF signal from the LNB is digitized by the high-speed analog-to-digital converters of the SDR and processed by its internal Field Programmable Gate Array (FPGA). Depending on the available space, the data can then be transferred via Universal Serial Bus (USB) 3.0 interface to a data acquisition system as a continuous stream, without segmentation or event-based triggering, to maintain an unbiased record of the RFI environment throughout the measurement campaign.

In parallel, a Global Positioning System (GPS) receiver mounted on the aircraft should record position and time information, including latitude, longitude, and altitude. Although there is no need to synchronize the SDR and GPS units, a temporal alignment with a resolution of one second is typically sufficient to associate the aircraft's geolocation with the recorded signal data.

5.2.3 Flight Route

The selection of an appropriate flight route is a critical element of the measurement campaign, as it directly determines the number, geometry, and temporal variability of interference events that can be observed. From a measurement perspective, maximizing the aircraft's radio horizon is desirable to capture aggregate emissions from a broad spatial distribution of FS transmitters. Higher flight altitudes enhance this visibility by increasing the LOS range and the number of FS transmitters operating with overlapping frequencies within the aircraft's reception cone, thereby improving the statistical representativeness of the collected data.

However, the attainable altitude is constrained by the choice of aircraft. Light aircraft commonly used in scientific measurement campaigns, such as the Cessna 172, typically cruise at altitudes between 2 000 m and 4 000 m above ground level. While these platforms do not reach the operational ceiling of commercial airliners, they offer a practical compromise between measurement complexity and cost. In contrast, high-altitude research aircraft such as DLR's HALO [92] (a modified Gulfstream G550) can exceed 15 000 m, though they entail significantly higher logistical and financial requirements.

Flight paths should be strategically aligned with terrestrial infrastructure where FS links are concentrated to maximize the likelihood of recording FS RFI. As illustrated in Fig. 29, FS deployment patterns correlate strongly with infrastructure such as cities and highways. Consequently, flight routes that parallel motorways are preferable, as these regions host dense FS deployments for backbone and point-to-point communication services.

In countries or regions where reliable information on FS station locations and frequency usage is not readily available, such as Germany, conducting a preliminary ground-based survey using the complete measurement system along the intended route is recommended. This test drive can help identify active FS links, verify spectrum usage, and detect locations with potential frequency overlap with the measurement setup. The insights gained from such a pre-flight survey support the optimal selection of flight paths and enhance the efficiency and relevance of the airborne measurement campaign.



Figure 62: Photograph of the radio tower in Schöngeising, Germany, located at 48.13199° North, 11.22407° East, from which fixed service interference was detected on 18th of October 2023 in the 18.2-18.7 GHz frequency band.

Such a ground base survey was conducted using the measurement setup proposed in Fig. 58, with a spectrum analyzer after the Multiplexer. The test drive was performed around the radio tower in Schöngeising, Germany (48.13199° North, 11.22407° East), depicted in Figs. 62 and 63. During the survey, a 500 MHz portion of the spectrum in the 18.2–20.2 GHz band was recorded using an open LNB without the monopole antenna. The LNB used a local oscillator frequency of 17.25 GHz, resulting in an IF centered at 1.025 GHz. FS RFI in the K- and Ka-bands was captured at two different locations as shown in the map in Fig. 64.

The screenshots of the spectrum analyzer are provided in Fig. 65 for measurement point No. 1 and Fig. 66 for measurement point No. 2. The plot shows three prominent FS carriers clearly above the noise floor, with an INR exceeding 10 dB for each signal at measurement point No. 2. The center frequencies and spectral shapes of the carriers correspond well to the expected FS channel raster defined in ERC Rec. 12-03, confirming its applicability in the observed frequency range. Each carrier occupies approximately 55 MHz of bandwidth, and the spacing between adjacent center frequencies is also approximately 55 MHz. According to ERC Rec. 12-03 [58], the center frequencies in this frequency range is $f_N = f_0 - 1000 + 55n$, where $f_0 = 18\,700$ MHz and $n = 1, \dots, 17$. Using $n = \{7, 9, 12\}$ would lead to the center frequencies of these three FS carriers transferred to the IF at $f_{IF} = \{835\text{ MHz}, 945\text{ MHz}, 1\,110\text{ MHz}\}$, inline with measurement. That confirms the assumption taken for the simulation model.



Figure 63: Photograph of the fixed service antennas on the radio tower in Schöngeising, Germany, located at 48.13199° North, 11.22407° East, from which fixed service interference was detected on 18th of October 2023 in the 18.2-18.7 GHz frequency band.

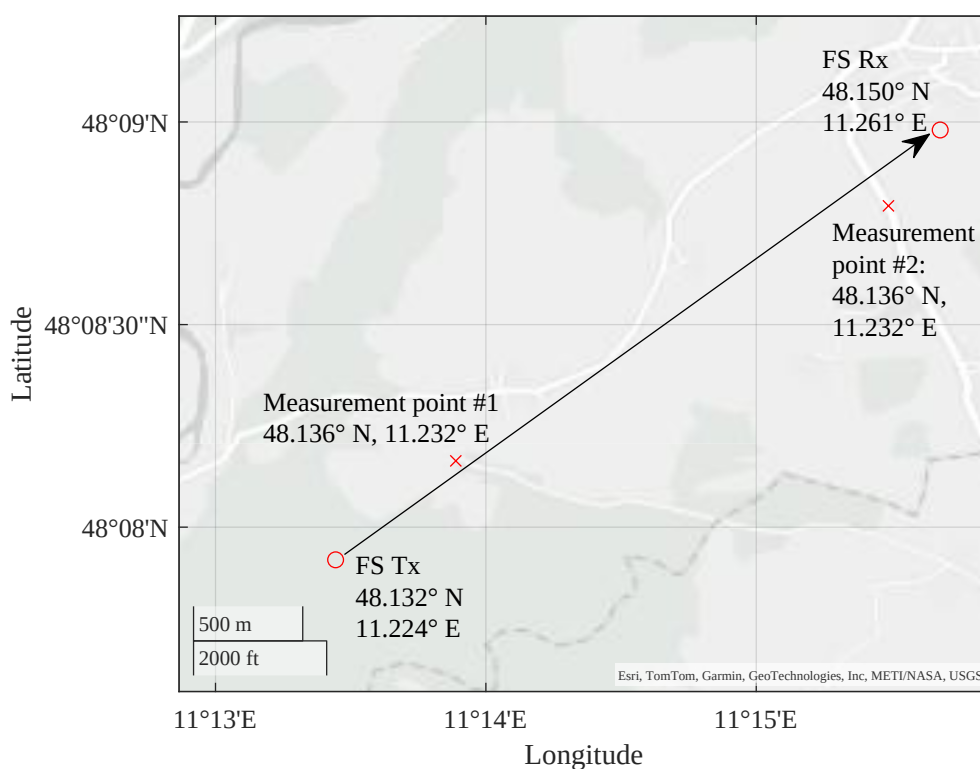


Figure 64: Map of the area around the radio tower in Schöngeising (FS Tx), showing the anticipated pointing direction of the transmitting fixed service antenna toward another fixed service station (FS Rx), as well as the two locations where spectrum analyzer measurements were taken.

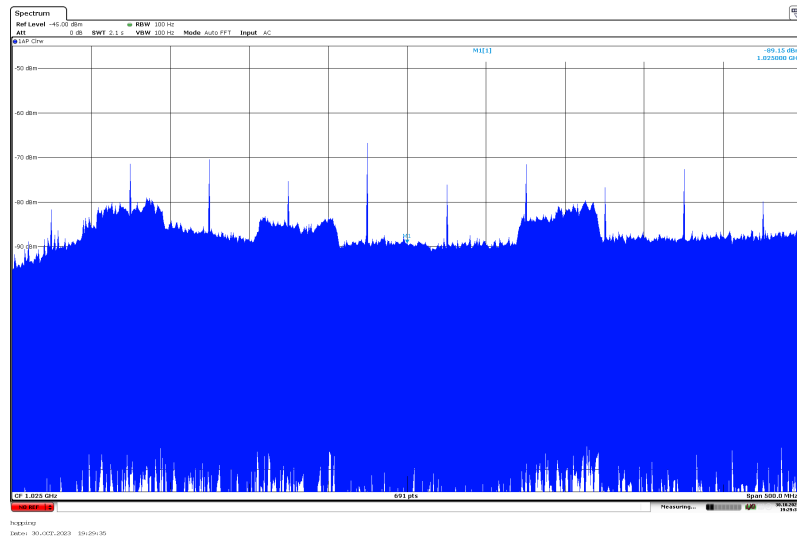


Figure 65: Spectrum analyzer screenshot at measurement point No. 1 showing three fixed service carriers above the noise floor confirming the visibility of fixed service interference and the application of harmonized channel raster defined in ERC Recommendation 12-03

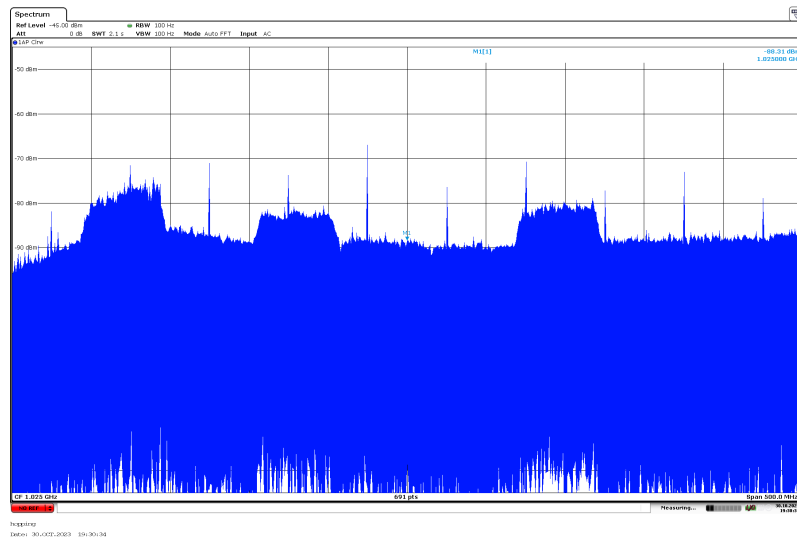


Figure 66: Spectrum analyzer screenshot at measurement point No. 2 showing three fixed service carriers above the noise floor confirming the visibility of fixed service interference and the application of harmonized channel raster defined in ERC Recommendation 12-03

The measurement was taken using an open LNB. Hence, the absolute levels of the FS carriers depend on the pointing direction of the open waveguide towards the antenna at the time the screenshot was taken. Despite this passive setup, the FS signals are distinctly visible, underscoring both the band activity and the measurement approach's effectiveness.

Key Takeaway

An airborne measurement setup to detect FS RFI should comprise a vertically mounted $\lambda/4$ monopole antenna, an LNB downconverter, an SDR, and an onboard recorder. Continuous complex I/Q sampling should be carried out in parallel with GPS logging, and the measurement bandwidth should be adjusted to meet storage constraints. The most critical point is the flight route, which should be selected to maximize visibility of FS stations with frequency overlap. Ground-based pre-surveys are recommended in regions lacking FS deployment data. A conducted ground-based survey in Schöngeising, Germany, recorded 500 MHz in the 18.2-20.2 GHz band and detected three FS carriers with INR values exceeding 10 dB. The observed channel spacing and IF frequencies matched the 55 MHz raster of ERC Rec. 12-03. They aligned with model assumptions, confirming both strong FS activity and the validity of the simulation and measurement approach.

5.3 Expected Measurement Results

To quantify the received interference levels during the airborne measurement campaign, an estimation of the expected measurement results is performed. Therefore, the expected received signal is processed to determine its total power within the operational receiver bandwidth of 10 MHz. As no synchronization or knowledge of the transmitted data is available, no channel estimation is performed. Instead, the focus lies on quantifying the aggregate interference power after filtering. The received complex baseband signal, consisting of the interference signal $\tilde{y}(t)$ and additive noise $\eta(t)$ is passed through a digital bandpass filter $h_B(t)$, which models the receiver's frequency response and limits the signal to the bandwidth of interest. This yields the filtered signal $\tilde{y}_B(t) = (\tilde{y}(t) + \eta(t)) * h_B(t)$. The signal is then sampled at a rate f_s , resulting in the discrete-time sequence $\tilde{y}_B[n] = \tilde{y}_B(nT_s)$, where $T_s = 1/f_s$ is the sampling interval. The signal component $\tilde{y}(t)$ is calculated according to (2.2).

To simulate the additive thermal noise in the receiver chain over the 10 MHz bandwidth, a complex-valued white Gaussian noise signal is generated in the baseband. The discrete-time noise samples are modeled as

$$\eta[n] = \eta_I[n] + j \cdot \eta_Q[n], \quad (5.3)$$

where $\eta_I[n]$ and $\eta_Q[n]$ are independent and identically distributed real-valued Gaussian random variables with zero mean and variance σ^2 , i.e.,

$$\eta_I[n], \eta_Q[n] \sim \mathcal{N}(0, \sigma^2). \quad (5.4)$$

This results in a circularly symmetric complex Gaussian process. The total noise power of the complex signal is given by

$$p_N = \mathbb{E}[|\eta[n]|^2] = \mathbb{E}[\eta_I[n]^2 + \eta_Q[n]^2] = 2\sigma^2. \quad (5.5)$$

The noise power p_N is selected based on the assumed receiver noise floor and distributed uniformly over the entire receiver bandwidth of 10 MHz.

To provide an estimation of interference levels, a FS RFI signal is superimposed on the simulated noise using the information on INR from Fig. 66. Considering $\text{INR} \leq 10$ dB the interference power is set to

$$\zeta \leq p_N \cdot 10^{\frac{\text{INR}}{10}} \leq 10p_N. \quad (5.6)$$

This allows the interference signal to be scaled accordingly before being added to the noise. After combining both components, the signal is normalized to the maximum observed value across the full time series. This max-normalization ensures that all output power values are represented on a relative scale, making temporal and spectral comparisons across datasets consistent.

Since the receiver bandwidth of 10 MHz is narrower than the 20 MHz assumed in simulation studies, some energy loss due to out-of-band interference components may occur. This constraint may lead to a slight underestimation of the total interference power in cases where fixed service transmitters operate across wider channels or where the interference spectrum is broader. The simulated FS characteristics are summarized in Table 14.

In the waterfall plot shown in Figure 67, the received signal's time-varying psd is visualized over a representative measurement interval. The vertical axis corresponds to the range around the center frequency of 18.195 GHz, while the horizontal axis indicates time. The color scale represents the relative psd after max-normalization, allowing the visualization of variations and persistent spectral components. Based on the underlying

Table 14: Potential fixed service transmit characteristics to be detected during the experimental measurement campaign

Parameters	Unit	Value
Center frequency of the FS band	MHz	$f_0 = 18\,195$
FS channel number		12
Bandwidth	MHz	55
Filter		Raised cosine
Roll-off factor		$\beta = 0.35$
Center frequency FS channel [58]	MHz	$f_n = 18\,360$
Max. interference-to-noise ratio	dB	INR = 10
Antenna gain	dBi	$G_{FS} = 37$
Antenna pattern		Rec. ITU-R F.1245
Antenna azimuth	degrees	$\Lambda_{FS} = 55$
Antenna elevation	degrees	$\varepsilon_{FS} = 1$
Antenna height	m	$h_{FS} = 50$

assumptions, the FS RFI is expected to exhibit a persistent signature over an extended period, particularly at lower flight altitudes where the angular range of the main lobe is traversed more slowly. This supports the increased likelihood of detecting fixed service carriers within the receiver’s bandwidth.

Key Takeaway

The simulated measurement of a 10 MHz bandwidth at low aircraft altitudes indicates that persistent FS RFI carriers would manifest as stable spectral components. They are dominant over extended periods in the time-frequency domain. Thus, FS RFI is detectable with the proposed setup. However, an in-flight measurement to apply this setup and validate the *AERO-FS* interference model could not be conducted within the resources available for this study, and it remains an open task.

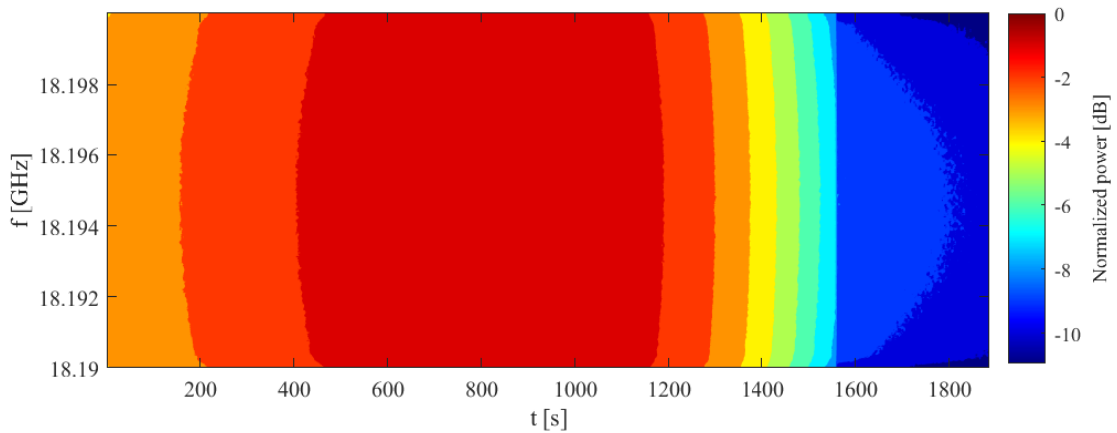


Figure 67: Power-density spectrum over time (waterfall plot) of a 1 800 second snapshot of a potential measurement flight at $h_{AC} = 1.5$ km and $v_{AC} = 220$ km/h across the radio tower in Schöngeising, Germany

6 Conclusion

6.1 Summary

This thesis quantified the impact of aggregate fixed service (FS) radio frequency interference (RFI) on an aeronautical-earth station in motion (A-ESIM) operating with networks in the geostationary satellite orbit (GSO) in the 17.7-19.7 GHz band. The main objective was to develop a scalable, regulation-compliant stochastic channel model enabling fast and reliable RFI estimation for performance assessments and in-flight entertainment (IFE) satellite communication (SATCOM) system design.

An analytical channel model for a representative en-route flight scenario was established, capturing both direct and reflected FS RFI components. Simulations based on real FS deployment data, complemented by International Telecommunication Union-Radiocommunication Sector (ITU-R) assumptions, showed that the dominant contribution is the line-of-sight path, with multipath components (MPCs) well below the receiver noise floor. The first-order statistics of the simulated interference follow a skewed normal distribution in the logarithmic domain, accurately approximated by a log-skew-normal (LSN) model.

Performance evaluation revealed that smaller A-ESIM antennas ($D_{AC}/\lambda < 50$) experience regulatory threshold exceedance more than half of the time, with long average fade durations, whereas larger antennas significantly reduce both occurrence and duration of harmful interference. Nevertheless, even for larger antennas, interference events remain operationally relevant, potentially degrading spectral efficiency below International Civil Aviation Organization (ICAO) objectives.

A higher-order finite state Markov chain (FSMC) model was derived from the simulated data using X -means clustering to balance accuracy and complexity. The resulting model reproduces first- and second-order statistics with a mean squared error (MSE) below 10^{-4} and supports scaling to different antenna diameters, center frequencies, and flight velocities without re-running the base simulation. An enhanced algorithm was introduced to better capture rare, high-interference states.

Finally, a concept for an airborne measurement campaign was proposed to experimentally validate the model, including platform selection, equipment specification, and flight route design. Preliminary ground measurements confirmed both the presence of FS RFI and the functionality of the proposed measurement setup. An in-flight measurement was not conducted so far.

The developed methodology provides a scalable and regulation-compliant interference model that supports robust A-ESIM SATCOM system design, informs regulatory coordination, and offers a basis for targeted interference mitigation strategies in the shared 17.7-19.7 GHz spectrum.

6.2 Future Perspectives

6.2.1 Measurement Campaign

A central direction for future work is executing the proposed airborne measurement campaign to validate and refine the simulation-based interference analysis. The results presented in this thesis provide a comprehensive statistical characterization of aggregate interference from terrestrial FS transmitters to aeronautical SATCOM terminals; however, they rely on assumptions regarding deployment densities, antenna characteristics, propagation environments, and temporal dynamics. While the ground survey confirmed the presence and detectability of FS RFI, in-flight validation has not yet been conducted.

Implementing the campaign as outlined in section 5.2 would yield empirical data for direct comparison with model predictions. Matching measured interference power levels, statistical properties, and spatial variability with simulation outputs would enable a final confirmation, and, if necessary, adjustment, of the developed model.

6.2.2 Non-GSO ESIMs

At WRC-23, the use of the K- and Ka-band frequency ranges by non-GSO A-ESIMs was adopted through Res. 123 (WRC-23)[93], covering the same applications as Res. 169 (Rev. WRC-23) but from a non-GSO perspective. For non-GSO systems, agile antenna pointing of the A-ESIM receiver must be modeled instead of a quasi-fixed elevation towards the GSO. The antenna elevation relative to the horizontal plane changes over time, and most large constellations (e.g., Amazon Kuiper, SpaceX Starlink) maintain a minimum elevation above 30 degrees, largely due to flat-panel antenna constraints. This higher minimum elevation improves isolation against FS RFI, as the back-lobe gain remains nearly constant at about -10 dBi for off-axis angles exceeding 30 degrees (cf. Fig. 31). Adapting the existing interference model to these dynamics offers a promising subject for further work.

In addition, non-GSO constellations comprising thousands of satellites inherently provide redundancy for ground-based terminals. This enables intelligent satellite selection strategies as a potential interference mitigation method. Prioritizing satellites at higher elevations is the most straightforward approach to reducing FS RFI, but such strategies must also respect the regulatory constraints for protecting GSO networks.

6.2.3 Narrow Band Emissions and Unmanned Aerial Vehicles

Similar modeling approaches can be extended to Ku-band frequencies, where the primary FSS allocations for A-ESIMs are regulated. In Res. 155 (Rev. WRC-23) [40], the use of FSS spectrum by UAS control and non-payload communication (CNPC) is regulated for various space-to-Earth frequency ranges across ITU regions. Employing FSS spectrum

for UAS applications such as beyond-LOS control adds a distinct set of challenges to the FS RFI problem, including safety-of-flight considerations, highly variable flight altitudes (from 100 m to 20 000 m), and random or dynamic flight paths. This high degree of mobility and operational variability intensifies interference management. For example, a UAS operating in a surveillance mode could repeatedly encounter FS RFI from the same source. The technical and operational characteristics of UAS differ from those of IFE systems, employing narrow-band emissions subject to the Doppler shift. Furthermore, the FS in the Ku-band often uses higher transmit powers than in the K- and Ka-bands, altering the interference impact in terms of availability, continuity, and integrity, especially in safety-critical operations.

6.2.4 Flat-Panel Antennas

The FS RFI model developed in this thesis is based on the technical and operational characteristics of A-ESIMs as the ITU recommends, particularly those outlined in Rep. ITU-R S.2464 [38]. Since its ratification in 2019, following a four-year study cycle from WRC-15 to WRC-19, most modern aircraft have transitioned to flat-panel antennas. These systems combine electronically steered beams with mechanical skew angles, resulting in more complex antenna patterns than the rotationally symmetric parabolic reflector pattern used as the regulatory reference limit.

Such differences in antenna radiation characteristics may significantly influence FS RFI levels, yet no official ITU reference patterns for FSS antenna arrays are currently available. Rec. ITU-R M.2101 [95] defines beamforming antenna patterns for terrestrial MS base stations and user terminals. Adapting and extending such models for GSO and non-GSO ESIMs would be a logical extension.

6.2.5 Machine Learning

The modeling and quantification of interference in this work rely on clustering algorithms and stochastic modeling techniques to generalize interference time series into manageable abstract states. Building on this foundation, machine learning (ML) approaches offer considerable potential for model refinement and operational decision-making.

Supervised learning methods could be trained on the simulation datasets to predict interference severity, considering additional degrees of freedom, incorporating mitigation methods like interference maps. Unsupervised techniques, including autoencoders or time-series clustering, may reveal hidden patterns in interference dynamics that classical state models fail to capture. Reinforcement learning could be leveraged to adapt antenna steering, beamforming, or coding strategies in real time, responding dynamically to predicted interference conditions.

Such approaches would require on-board, real-time environmental estimation and decision-making under uncertainty, capabilities increasingly enabled by advances in edge artificial intelligence (AI) and integrated avionics [96]. From a regulatory perspective, ML-based models could also support compliance mapping by estimating the probability of meeting protection criteria under varying operational conditions, thereby contributing to more efficient spectrum use for ESIMs.

6.2.6 Extension of 6G NTN Model

The emerging 6G non-terrestrial networks (NTN) architecture envisions the seamless integration of satellite, aerial, and terrestrial segments to enable global, resilient connectivity. While current 6G NTN frameworks focus primarily on service provision from satellite constellations to ground terminals, extending these models to capture interference interactions in spectrum-sharing scenarios, particularly in mixed spectrum environments, is useful.

The results of this thesis provide a basis for such extensions by quantifying how aeronautical terminals operating in co-frequency bands with terrestrial FS experience highly dynamic, location-dependent interference. An enhanced 6G NTN model could incorporate asymmetric protection requirements defined by spectrum regulations and probabilistic link impairments from terrestrial sources. Integrating such an interference model into end-to-end system simulators would enable researchers and regulators to assess the impact on quality of service, especially for vertical applications such as airborne emergency services or real-time communications.

6.2.7 Correlation of Rain Attenuation in the Propagation Paths

In K- and Ka-band aeronautical SATCOM systems, rain attenuation is a critical factor, especially along slant paths traversing the troposphere. While current models often assume independent fading on different links, realistic propagation conditions frequently introduce spatial correlation, particularly when the link from the aircraft to the satellite and the interfering air-to-ground path intersect the same rain volume. This correlation becomes especially relevant when the aircraft flies below the rain height, as both paths may go through the same rain cell. As a result, the attenuation of the desired signal and the interfering FS link may become statistically dependent, complicating performance predictions.

However, existing recommendations such as ITU-R P.618 do not account for cross-link rain correlation. Future work could focus on developing and validating statistical models that capture this spatial correlation.

Appendix A

Antenna Reference Pattern Recommendation ITU-R S.580-6

If $D/\lambda \geq 50$:

$$G(\varphi) = \begin{cases} G_{\max} - 2.5 \cdot 10^{-3}(D/\lambda \cdot \varphi)^2 & 0 \leq \varphi < \varphi_m \\ G_1 & \varphi_m \leq \varphi < \varphi_r \\ 29 - 25 \log_{10} \varphi & \varphi_r \leq \varphi < 19.95 \\ \min(-3.5, 32 - 25 \log_{10} \varphi) & 19.95 \leq \varphi < \varphi_b \\ -10 & \varphi_b \leq \varphi \leq 180 \end{cases} \quad (\text{A.1})$$

If $D/\lambda < 50$:

$$G = (\varphi) \begin{cases} G_{\max} - 2.5 \cdot 10^{-3}(D/\lambda \cdot \varphi)^2 & 0 \leq \varphi < \varphi_m \\ G_1 & \varphi_m \leq \varphi < \varphi_r \\ 52 - 10 \log_{10} D/\lambda - 25 \log_{10} \varphi & \varphi_r \leq \varphi < \varphi_b \\ 10 - 10 \log_{10} D/\lambda & \varphi_b \leq \varphi \leq 180 \end{cases} \quad (\text{A.2})$$

where

$$D/\lambda = \sqrt{\frac{10^{(\frac{G_{\max}}{10})}}{\eta \pi^2}} \quad (\text{A.3})$$

$$\varphi_m = 20\lambda/D \sqrt{G_{\max} - G_1} \quad (\text{A.4})$$

$$G_1 = \begin{cases} 2 + 15 \log_{10}(D/\lambda) & D/\lambda < 50 \\ -21 + 25 \log_{10}(D/\lambda) & 50 \leq D/\lambda < 100 \\ -1 + 15 \log_{10}(D/\lambda) & 100 \leq D/\lambda \end{cases} \quad (\text{A.5})$$

$$\varphi_r = \begin{cases} 15.85(D/\lambda)^{-0.6} & D/\lambda \geq 100 \\ 100\lambda/D & D/\lambda < 100 \end{cases} \quad (\text{A.6})$$

$$\varphi_b = 10^{\frac{45}{25}} \quad (\text{A.7})$$

Appendix B

Determination of Simulation Time Step

The change of the receive signal levels due to FS RFI is caused by the changing geometry between the aircraft and the respective FS station antenna boresights. The main interest is the definition of the time step in such a way that the peaks of the FS interference caused by the main beams of the FS stations are captured with a predefined accuracy. Hence, the time step must be chosen, ensuring that the difference in the FS RFI levels between two waypoints does not exceed a defined threshold. The time step is calculated from the

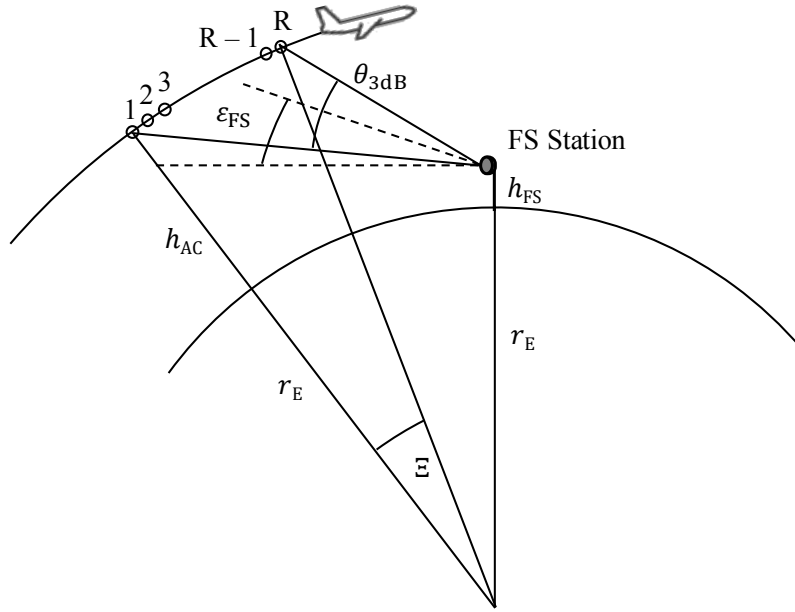


Figure 68: Parameters and notations for determining the necessary time step for a specific accuracy

formula of the flight velocity $v_{AC} = s/t$, with s as the flight path being the secant of a circular segment $s = \Xi \cdot (r_E + h_{AC})$. Ξ is the central angle of the circular segment in radians according to Fig. 68. When performing a time-d discrete simulation, the elapsed simulation time is n -times a time step, $t = n\Delta t$. Hence, the time step is calculated by

$$\Delta t = \frac{(r_E + h_{AC}) \cdot \Xi}{n \cdot v_{AC}}. \quad (B.1)$$

The relative change of the RFI is synonymous with the slope of the FS antenna main lobe. The first derivative of the antenna gain can determine it. With the relative gain of -3 dB being within the main lobe, the derivative from the FS antenna gain envelope [51] can be calculated

$$\begin{aligned} \frac{\partial G}{\partial \theta} &= \partial(G_{\max} - 2.5 \cdot 10^{-3} \left(\frac{D_{FS}}{\lambda} \theta\right)^2) / \partial \theta \\ &= -5 \cdot 10^{-3} \left(\frac{D_{FS}}{\lambda}\right)^2 \theta. \end{aligned} \quad (B.2)$$

The relative change ΔG can be determined from (B.2) to

$$\Delta G = \left| -5 \cdot 10^{-3} \left(\frac{D_{\text{FS}}}{\lambda} \right)^2 \theta \Delta \theta \right| \quad (\text{B.3})$$

with the angular increment $\Delta \theta = \theta_{3\text{dB}}/n$ being defined by the number of steps n in the half power beam width of the narrowest FS antenna. Furthermore, the highest interference from the FS station will be detected. According to Fig. 11, it occurs at the beam peak of the FS station antenna. In case of n steps within $\theta_{3\text{dB}}$, the beam peak is expected to occur in the middle at $\theta = \theta_{3\text{dB}}/(2n)$. Putting these two considerations into (B.3) the relative change is calculated by

$$\Delta G = \frac{\theta_{3\text{dB}}^2}{2n^2} 5 \cdot 10^{-3} \left(\frac{D_{\text{FS}}}{\lambda} \right)^2. \quad (\text{B.4})$$

The half power beam width can also be derived from the formula of the main lobe gain in (B.2), setting $G = G_{\text{max}} - 3$ dB and solving the equation for θ . The half power beam width is, in this case, $\theta_{3\text{dB}} = 2\theta$. Putting this result into (B.4) and solve the equation for n :

$$n = \sqrt{\frac{12}{\Delta G}}. \quad (\text{B.5})$$

Putting (B.5) into (B.1) gets the dependency of the required time step Δt as a function of the flight altitude h_{AC} , the accuracy ΔG and the flight velocity v_{AC} .

$$\Delta t = \sqrt{\frac{\Delta G}{12}} \frac{\Xi}{v_{\text{AC}}} (r_{\text{E}} + h_{\text{AC}}). \quad (\text{B.6})$$

The angle Ξ can be calculated by the geometric relations of the triangles and provides additional dependencies on the max. FS station antenna height h_{FS} , the half power beam width of the FS station $\theta_{3\text{dB}}$ and the maximum FS elevation angle ε_{FS} .

$$\begin{aligned} \Xi = & \sin^{-1} \left(\frac{r_{\text{E}} + h_{\text{FS}}}{r_{\text{E}} + h_{\text{AC}}} \cos \left(\varepsilon_{\text{FS}} + \frac{\theta_{3\text{dB}}}{2} \right) \right) \\ & - \sin^{-1} \left(\frac{r_{\text{E}} + h_{\text{FS}}}{r_{\text{E}} + h_{\text{AC}}} \cos \left(\varepsilon_{\text{FS}} - \frac{\theta_{3\text{dB}}}{2} \right) \right) + \theta_{3\text{dB}}. \end{aligned} \quad (\text{B.7})$$

Using the characteristics from Table 9 and defining a required accuracy of $\Delta G = 0.5$ dB, time step of $\Delta t = 0.143$ s is calculated, which is rounded to be $\Delta t = 0.1$ s to be used for the simulation.

The application of (B.6) is illustrated in Fig.69 for varying aircraft characteristics and in Fig.70 for varying FS characteristics, both showing the required time steps to achieve an accuracy of 0.5dB in the FS RFI power ζ .

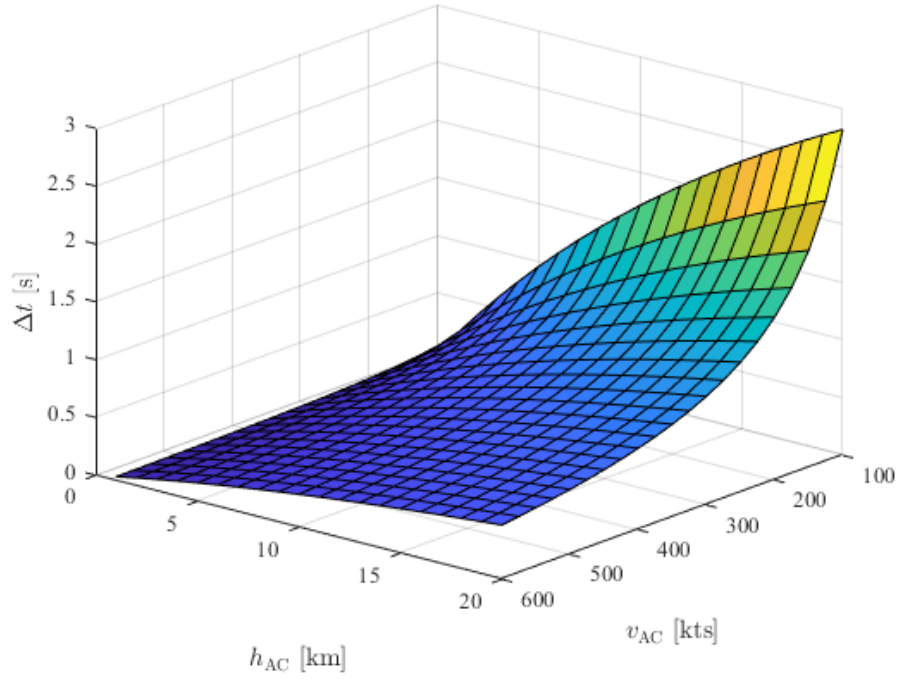


Figure 69: Required time steps to achieve an accuracy of 0.5 dB as a function of the aircraft flight altitude and velocity.

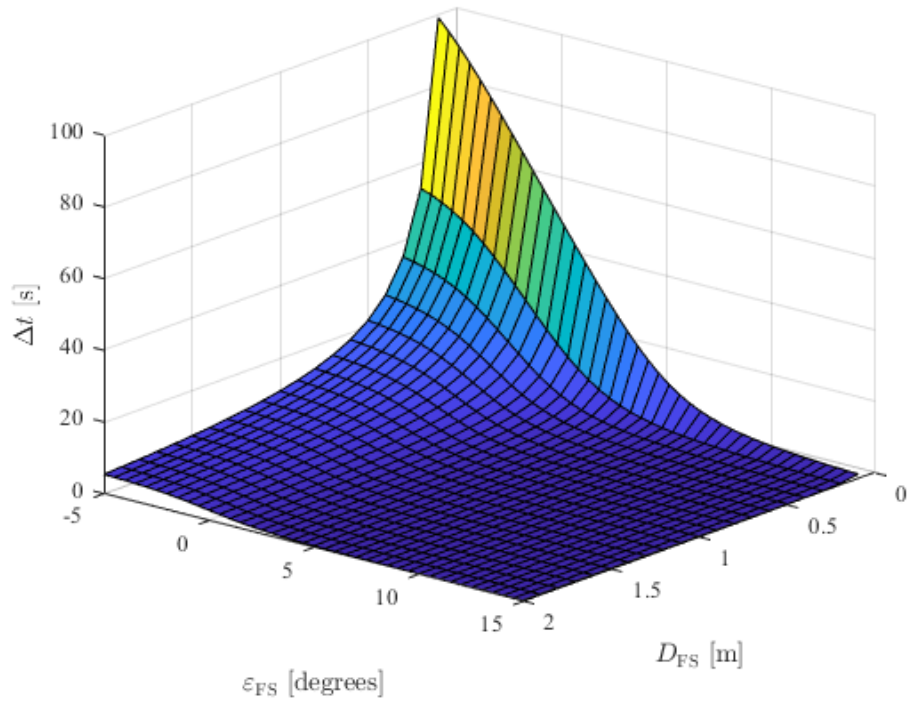


Figure 70: Required time steps to achieve an accuracy of 0.5 dB as a function of fixed service antenna diameter and elevation.

Appendix C
Transition Probability Matrix $D/\lambda \geq 50$

$$T_{\circ} = \begin{bmatrix} 0.998 & 0 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0.995 & 0.001 & 0.003 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0.001 & 0.002 & 0.997 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0.002 & 0 & 0.993 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.004 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0.986 & 0 & 0.006 & 0 & 0 & 0 & 0 & 0.008 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0.429 & 0.143 & 0.286 & 0.143 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0.008 & 0 & 0.987 & 0.005 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.008 & 0.988 & 0.004 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.007 & 0.991 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.005 & 0.995 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.986 & 0.006 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0.005 & 0 & 0 & 0 & 0 & 0 & 0 & 0.008 & 0.986 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.991 & 0 & 0.003 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \\ 0 & 0 & 0 & 0.003 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.005 & 0 & 0.992 & 0 & 0 & \dots 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots 0 \end{bmatrix} \quad (C.1)$$

Appendix D
Transition Probability Matrix $D/\lambda < 50$

$$\mathbf{T}_o = \begin{bmatrix}
 0.998 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0.001 & 0.997 & 0 & 0 & 0 & 0 & 0 & 0 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.143 & 0 & 0 & 0 & 0 & 0.071 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0.990 & 0 & 0.006 & 0.004 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0.992 & 0 & 0.006 & 0 & 0 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0.004 & 0 & 0.991 & 0 & 0 & 0 & 0 & 0.006 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0.007 & 0.002 & 0 & 0.991 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0.750 & 0.250 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 & 0.994 & 0 & 0 & 0 & 0 & 0 & 0.003 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0.005 & 0 & 0 & 0 & 0 & 0.995 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0.004 & 0 & 0 & 0 & 0 & 0.990 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.993 & 0 & 0 & 0.003 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.986 & 0 & 0 & 0 & 0 & 0.007 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0.143 & 0 & 0 & 0 & 0.429 & 0 & 0.429 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.002 & 0 & 0 & 0.003 & 0 & 0 & 0.994 & 0 & 0 & 0 & 0 & \dots & 0 \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dots & 0
 \end{bmatrix} \tag{D.1}$$

Appendix E
Cluster Center $D/\lambda \geq 50$

$$\begin{aligned}
 \mathbf{S} = & \left\{ \begin{bmatrix} -163.3 \\ -163.3 \end{bmatrix}, \begin{bmatrix} -160.9 \\ -160.9 \end{bmatrix}, \begin{bmatrix} -162 \\ -162 \end{bmatrix}, \begin{bmatrix} -159.9 \\ -159.9 \end{bmatrix}, \begin{bmatrix} -140.4 \\ -140.4 \end{bmatrix}, \begin{bmatrix} -148.3 \\ -162.1 \end{bmatrix}, \begin{bmatrix} -138.7 \\ -138.7 \end{bmatrix}, \begin{bmatrix} -136.7 \\ -136.7 \end{bmatrix}, \begin{bmatrix} -133.3 \\ -133.3 \end{bmatrix}, \begin{bmatrix} -128.4 \\ -128.4 \end{bmatrix}, \right. \\
 & \begin{bmatrix} -142.9 \\ -142.9 \end{bmatrix}, \begin{bmatrix} -141.8 \\ -141.8 \end{bmatrix}, \begin{bmatrix} -158.5 \\ -158.5 \end{bmatrix}, \begin{bmatrix} -145.7 \\ -149.7 \end{bmatrix}, \begin{bmatrix} -159.2 \\ -159.2 \end{bmatrix}, \begin{bmatrix} -151.3 \\ -138 \end{bmatrix}, \begin{bmatrix} -144.7 \\ -144.7 \end{bmatrix}, \begin{bmatrix} -157.3 \\ -157.3 \end{bmatrix}, \begin{bmatrix} -158.6 \\ -147.3 \end{bmatrix}, \begin{bmatrix} -149.2 \\ -149.2 \end{bmatrix}, \\
 & \begin{bmatrix} -143.9 \\ -143.9 \end{bmatrix}, \begin{bmatrix} -157.8 \\ -157.8 \end{bmatrix}, \begin{bmatrix} -154.8 \\ -157.3 \end{bmatrix}, \begin{bmatrix} -156.3 \\ -156.3 \end{bmatrix}, \begin{bmatrix} -158.6 \\ -156.6 \end{bmatrix}, \begin{bmatrix} -146.7 \\ -146.7 \end{bmatrix}, \begin{bmatrix} -157.5 \\ -155.5 \end{bmatrix}, \begin{bmatrix} -145.5 \\ -145.5 \end{bmatrix}, \begin{bmatrix} -156.6 \\ -158.5 \end{bmatrix}, \begin{bmatrix} -155.9 \\ -155.9 \end{bmatrix}, \\
 & \begin{bmatrix} -146.1 \\ -146.1 \end{bmatrix}, \begin{bmatrix} -157.9 \\ -160.9 \end{bmatrix}, \begin{bmatrix} -156.8 \\ -156.8 \end{bmatrix}, \begin{bmatrix} -148.1 \\ -148.1 \end{bmatrix}, \begin{bmatrix} -148 \\ -150.5 \end{bmatrix}, \begin{bmatrix} -147.7 \\ -147.7 \end{bmatrix}, \begin{bmatrix} -155.2 \\ -155.2 \end{bmatrix}, \begin{bmatrix} -154.8 \\ -154.8 \end{bmatrix}, \begin{bmatrix} -155.7 \\ -154.5 \end{bmatrix}, \begin{bmatrix} -156.4 \\ -155.4 \end{bmatrix}, \\
 & \begin{bmatrix} -153.1 \\ -146 \end{bmatrix}, \begin{bmatrix} -161.3 \\ -154.3 \end{bmatrix}, \begin{bmatrix} -145.5 \\ -154.4 \end{bmatrix}, \begin{bmatrix} -155.5 \\ -155.5 \end{bmatrix}, \begin{bmatrix} -154.2 \\ -154.2 \end{bmatrix}, \begin{bmatrix} -149 \\ -146.5 \end{bmatrix}, \begin{bmatrix} -147.2 \\ -147.2 \end{bmatrix}, \begin{bmatrix} -150.7 \\ -148.1 \end{bmatrix}, \begin{bmatrix} -153.5 \\ -158.9 \end{bmatrix}, \begin{bmatrix} -155.1 \\ -156.1 \end{bmatrix}, \\
 & \begin{bmatrix} -148.5 \\ -148.5 \end{bmatrix}, \begin{bmatrix} -154 \\ -154.8 \end{bmatrix}, \begin{bmatrix} -154.5 \\ -155.4 \end{bmatrix}, \begin{bmatrix} -154.5 \\ -154.5 \end{bmatrix}, \begin{bmatrix} -151.5 \\ -149.4 \end{bmatrix}, \begin{bmatrix} -154 \\ -154 \end{bmatrix}, \begin{bmatrix} -149.6 \\ -150.5 \end{bmatrix}, \begin{bmatrix} -148.7 \\ -153.8 \end{bmatrix}, \begin{bmatrix} -149.5 \\ -149.5 \end{bmatrix}, \begin{bmatrix} -158.5 \\ -150.8 \end{bmatrix}, \\
 & \begin{bmatrix} -153.2 \\ -148.2 \end{bmatrix}, \begin{bmatrix} -156 \\ -157 \end{bmatrix}, \begin{bmatrix} -148.9 \\ -148.9 \end{bmatrix}, \begin{bmatrix} -153.7 \\ -153.7 \end{bmatrix}, \begin{bmatrix} -150.7 \\ -150.7 \end{bmatrix}, \begin{bmatrix} -149.8 \\ -149.8 \end{bmatrix}, \begin{bmatrix} -153.5 \\ -153.5 \end{bmatrix}, \begin{bmatrix} -149 \\ -149.8 \end{bmatrix}, \begin{bmatrix} -153.1 \\ -156.4 \end{bmatrix}, \begin{bmatrix} -151.5 \\ -151.5 \end{bmatrix}, \\
 & \left. \begin{bmatrix} -149.8 \\ -157.7 \end{bmatrix}, \begin{bmatrix} -152.3 \\ -152.3 \end{bmatrix}, \begin{bmatrix} -156.8 \\ -153.7 \end{bmatrix}, \begin{bmatrix} -150.2 \\ -150.2 \end{bmatrix}, \begin{bmatrix} -151.4 \\ -154.8 \end{bmatrix}, \begin{bmatrix} -151.8 \\ -152.9 \end{bmatrix}, \begin{bmatrix} -152.1 \\ -150.6 \end{bmatrix}, \begin{bmatrix} -154.4 \\ -153.7 \end{bmatrix}, \dots, \begin{bmatrix} -153.4 \\ -152.9 \end{bmatrix} \right\}
 \end{aligned} \tag{E.1}$$

Appendix F
Cluster Center $D/\lambda < 50$

$$\begin{aligned}
 \mathbf{S} = & \left\{ \begin{aligned} & \begin{bmatrix} -155.7 \\ -155.7 \end{bmatrix}, \begin{bmatrix} -154 \\ -154 \end{bmatrix}, \begin{bmatrix} -151.7 \\ -138.7 \end{bmatrix}, \begin{bmatrix} -131.3 \\ -131.3 \end{bmatrix}, \begin{bmatrix} -124 \\ -124 \end{bmatrix}, \begin{bmatrix} -133.1 \\ -133.1 \end{bmatrix}, \begin{bmatrix} -129.2 \\ -129.2 \end{bmatrix}, \begin{bmatrix} -140.8 \\ -155.5 \end{bmatrix}, \begin{bmatrix} -152.6 \\ -152.6 \end{bmatrix}, \begin{bmatrix} -118.6 \\ -118.6 \end{bmatrix}, \\ & \begin{bmatrix} -134.3 \\ -134.3 \end{bmatrix}, \begin{bmatrix} -150.7 \\ -150.7 \end{bmatrix}, \begin{bmatrix} -136.2 \\ -136.2 \end{bmatrix}, \begin{bmatrix} -145 \\ -134.6 \end{bmatrix}, \begin{bmatrix} -151.6 \\ -151.6 \end{bmatrix}, \begin{bmatrix} -152 \\ -149.4 \end{bmatrix}, \begin{bmatrix} -134.7 \\ -142.3 \end{bmatrix}, \begin{bmatrix} -137.1 \\ -137.1 \end{bmatrix}, \begin{bmatrix} -149.4 \\ -149.4 \end{bmatrix}, \begin{bmatrix} -148.8 \\ -148.8 \end{bmatrix}, \\ & \begin{bmatrix} -135.3 \\ -135.3 \end{bmatrix}, \begin{bmatrix} -150 \\ -150 \end{bmatrix}, \begin{bmatrix} -148.1 \\ -146.4 \end{bmatrix}, \begin{bmatrix} -149.4 \\ -147.3 \end{bmatrix}, \begin{bmatrix} -139.1 \\ -139.1 \end{bmatrix}, \begin{bmatrix} -148.3 \\ -148.3 \end{bmatrix}, \begin{bmatrix} -152.2 \\ -143.8 \end{bmatrix}, \begin{bmatrix} -137.8 \\ -137.8 \end{bmatrix}, \begin{bmatrix} -149.8 \\ -153 \end{bmatrix}, \begin{bmatrix} -138.5 \\ -138.5 \end{bmatrix}, \\ & \begin{bmatrix} -140.8 \\ -138.9 \end{bmatrix}, \begin{bmatrix} -147.8 \\ -147.8 \end{bmatrix}, \begin{bmatrix} -147.4 \\ -147.4 \end{bmatrix}, \begin{bmatrix} -141.7 \\ -141.7 \end{bmatrix}, \begin{bmatrix} -140.6 \\ -140.6 \end{bmatrix}, \begin{bmatrix} -139.6 \\ -139.6 \end{bmatrix}, \begin{bmatrix} -146.2 \\ -146.2 \end{bmatrix}, \begin{bmatrix} -148.7 \\ -150.4 \end{bmatrix}, \begin{bmatrix} -146.6 \\ -146.6 \end{bmatrix}, \begin{bmatrix} -144.1 \\ -138.9 \end{bmatrix}, \\ & \begin{bmatrix} -137.4 \\ -146 \end{bmatrix}, \begin{bmatrix} -146.2 \\ -143.5 \end{bmatrix}, \begin{bmatrix} -138.8 \\ -141.9 \end{bmatrix}, \begin{bmatrix} -147 \\ -147 \end{bmatrix}, \begin{bmatrix} -140.2 \\ -140.2 \end{bmatrix}, \begin{bmatrix} -145.6 \\ -151 \end{bmatrix}, \begin{bmatrix} -147.3 \\ -148.9 \end{bmatrix}, \begin{bmatrix} -138.9 \\ -150.1 \end{bmatrix}, \begin{bmatrix} -145.5 \\ -145.5 \end{bmatrix}, \begin{bmatrix} -141.9 \\ -141.9 \end{bmatrix}, \\ & \begin{bmatrix} -145.3 \\ -145.3 \end{bmatrix}, \begin{bmatrix} -148.7 \\ -140 \end{bmatrix}, \begin{bmatrix} -146.7 \\ -147.7 \end{bmatrix}, \begin{bmatrix} -146.3 \\ -145.6 \end{bmatrix}, \begin{bmatrix} -140.5 \\ -142.2 \end{bmatrix}, \begin{bmatrix} -145.8 \\ -145.8 \end{bmatrix}, \begin{bmatrix} -140.1 \\ -144 \end{bmatrix}, \begin{bmatrix} -142 \\ -141.2 \end{bmatrix}, \begin{bmatrix} -144.8 \\ -144.8 \end{bmatrix}, \begin{bmatrix} -141.4 \\ -141.4 \end{bmatrix}, \\ & \begin{bmatrix} -145.9 \\ -141.7 \end{bmatrix}, \begin{bmatrix} -145.4 \\ -148.3 \end{bmatrix}, \begin{bmatrix} -143.1 \\ -143.1 \end{bmatrix}, \begin{bmatrix} -145 \\ -145 \end{bmatrix}, \begin{bmatrix} -141 \\ -141 \end{bmatrix}, \begin{bmatrix} -148.9 \\ -143.8 \end{bmatrix}, \begin{bmatrix} -142 \\ -139.9 \end{bmatrix}, \begin{bmatrix} -145.4 \\ -146.3 \end{bmatrix}, \begin{bmatrix} -142.4 \\ -142.4 \end{bmatrix}, \begin{bmatrix} -146 \\ -147 \end{bmatrix}, \\ & \begin{bmatrix} -147.2 \\ -145.3 \end{bmatrix}, \begin{bmatrix} -143 \\ -149.1 \end{bmatrix}, \begin{bmatrix} -143.9 \\ -143.9 \end{bmatrix}, \begin{bmatrix} -144.8 \\ -143 \end{bmatrix}, \begin{bmatrix} -142.9 \\ -142.9 \end{bmatrix}, \begin{bmatrix} -145.1 \\ -144.1 \end{bmatrix}, \begin{bmatrix} -142.8 \\ -141.7 \end{bmatrix}, \begin{bmatrix} -142.2 \\ -142.2 \end{bmatrix}, \begin{bmatrix} -143.1 \\ -144.5 \end{bmatrix}, \dots, \begin{bmatrix} 0 \\ 0 \end{bmatrix} \end{aligned} \right\}
\end{aligned}
\tag{F.1}$$

List of Operators and Symbols

List of Operators

$\arg(\cdot)$	argument of a set of variables
$\max(\cdot)$	maximum of a set of variables
$\min(\cdot)$	minimum of a set of variables
$ \cdot $	absolute value of a scalar
$T(\cdot, \cdot)$	Owen's T function
$\text{erf}(\cdot)$	error function
$\exp(\cdot)$	exponential function
$\ \cdot\ ^2$	Euclidean norm, L2-Norm
$\lfloor \cdot \rfloor$	the floor operation
$\mathcal{N}(\cdot)$	normal distributed random variable
$\mathcal{U}(\cdot)$	uniform distributed random variable
$\mathcal{R}(\sigma_d)$	Rayleigh distributed random variable with variance σ_d
$\partial/\partial a$	derivative of a
$\text{Var}(\cdot)$	Variance
$\text{Pr}(\cdot)$	Probability of value

List of Constants

c_0	speed of light in vacuum	299 792 458 m/s
r_E	radius of the Earth	6 378.145 km
r_{GSO}	radius of the geostationary satellite orbit	42 164.2 km
k_B	Boltzmann constant	-228.6 dB(J/K)
e	Euler's number	2.71828
$j = \sqrt{-1}$	imaginary unit	
π	Pi	3.1415926
N_0	average global mean value of atmospheric refractivity extrapolated to sea level	315
ω_e	angular rate of rotation of the Earth	$4.178\,074\,582\,3 \cdot 10^{-3}$ deg./s

List of Most Important Symbols and Parameters

α	constant attenuation factor of the for a frequency flat channel
γ_1	angle between the velocity vector v of the receiver and the optical path towards the transmitter
γ_1	skewness of a skew normal distribution
δ	Dirac delta function
η	noise
η_{se}, η_{AC}	efficiency, spectral, aircraft antenna
$\varepsilon, \varepsilon_{AC}, \varepsilon_{FS}$	antenna elevation, aircraft, fixed service station
ε_r	complex relative permittivity
$\Delta\varphi_n$	phase difference on the n th propagation path
ϕ, ϕ	spatial off-axis angle of the direct
ϕ	spatial angle between the aircraft antenna pointing vector and a fixed service station
$\phi_{\mathcal{N}}, \Phi_{\mathcal{N}}$	probability distribution and cumulative distribution function of the normal distribution
$\Gamma, \Gamma_{hh}, \Gamma_{vv}, \Gamma_{Cv}, \Gamma_{Rh}, \Gamma_{Lh}$	Fresnel reflection coefficients for different polarization
κ	parametric ellipse angle
λ	carrier wavelength
Λ_{FS}	antenna azimuth of the fixed service station
μ_c	cluster center in K -means
ρ	root mean square of the surface height
σ	standard deviation of logarithmic values
σ_d	variance of Rayleigh distribution
Σ_c	Covariance matrix
τ	delay
θ_{3dB}	3 dB antenna beamwidth
θ_m	spatial angle between the fixed service station antenna pointing vector and the aircraft
ϑ	rotation angle of the Fresnel ellipse with respect to the center coordinates system
τ_d	delay on a propagation path d
Θ_m	spatial angle from the aircraft below the horizontal plane
ξ, ω, α, μ	location, scale, shape, expected value of a skew normal distribution
ζ	fixed service interference power
$\Delta\zeta$	difference in fixed service interference powers
a	semi-major axis Fresnel ellipsoid
$a_n, a_n^{LOS}, a_n^{co}, a_n^{nco}$	linear channel gain on the n th propagation path, line-of-sight, coherent/specular, non-coherent

a_L, a_F, a_T, a_P	losses in the linear domain, free space path loss, fuselage, propagation, polarization
$A_T(p), A_G(p), A_R(p), A_C(p), A_S(p)$	propagation losses in the logarithmic domain for a probability p , total, gas, rain, cloud, scintillation
A_{FL}	loss in the logarithmic domain, feeder loss
$a_B^{\text{tot}}(f), a_B^{\text{FSS}}(f), a_B^{\text{FS}}(f)$	out-of-band attenuation at a frequency f , total, fixed-satellite receiver, fixed service transmitter
b	semi-minor axis Fresnel ellipsoid
$B_{AC}, B^o, B_o, B_n, B_{\text{ref}}$	bandwidth, aircraft receiver, overlapping, occupied, necessary, reference
B_D	Doppler spread
C	Cost function to determine the complexity of a model
D, D_{AC}, D_{FS}	antenna diameter, aircraft, fixed service station
D_p	polarization decoupling
$\mathcal{D}$	set of training data
$d^{\text{RH}}, d^r, d^o, d_{\text{ortho}}$	distance, radio horizon, refracted, optical, orthodromic
d_m	distance of the line-of sight propagation path
d', d_m	distance of the reflected path
f_1, f_2	Debye relaxation frequencies
f, f_c, f_D, f_m	frequency, center, Doppler, fixed service station transmit
F	frequency offset from the edge of the total assigned band
g_{AC}, g_{FS}	antenna gain in the linear domain, aircraft, fixed service station
$G_{AC}, G_{FS}, G_{\text{max}}, G_1, G_{\text{di}}$	antenna gain in the logarithmic domain, aircraft, fixed service station, maximum, first side lobe, dipole
ΔG	gain difference
$h, h_{AC}, h_{FS}, h_c, h_R$	altitude, aircraft, fixed service station antenna, critical, rain
$h, \tilde{h}$	complex channel impulse response, wanted signals, unwanted signals
i	counter
I	interference power
k_e	effective Earth radius factor
K, K_{max}	number-, maximum number of states in a Markov chain
$K(\cdot)$	arbitrary probability density function used as a Kernel for density estimation
l	discrete time step
$\hat{l}(\mathcal{D})$	maximum log-likelihood estimate of data $\mathcal{D}$
L_{GSO}	geostationary satellite orbit longitude
L_s	slant range
$\text{Lat}, \text{Lat}_a, \text{Lat}_e$	latitude, start, end
$\text{Lon}, \text{Lon}_a, \text{Lon}_e$	longitude, start, end
ΔL	difference in longitude
M	number of visible fixed service stations
M_g	vegetation gravimetric water content
$\mathcal{M}$	Model representing a data set $\mathcal{D}$
N	total number of propagation paths, samples

N_S	number of states in a sequence of K states of a Markov chain
n	refractive index of the atmosphere
O	order of a higher order Markov chain
p	probability not to be exceeded
$p^I, p_{\text{rx}}, p_{\text{GSO}}, p_{\text{N}}$	power in the linear domain, interference, receive, geostationary satellite orbit, noise
p_q	number of free parameter in the model $\mathcal{M}_q$
psd^I	interfering power-spectral density
P^I	power in the logarithmic domain, interference
Q	total number of models $\mathcal{M}$
r_{eff}	effective radius of the Earth
r_s	surface roughness
R, R_c	number of simulation samples, samples assigned to a cluster
s, s_{AC}	distance, aircraft
S, S_c	set of states of a Markov chain
$\mathbb{S}, \tilde{\mathbb{S}}$	alphabets of symbols with equal probability of occurrence
Δt	time step
T, T_{N}	Temperature, noise
$\mathbf{T}$	transition probability matrix
$t, \dot{t}$	time, observation, excitation
u	scaling parameter controlling the smoothness of Kernel density estimate
v, v_{AC}	velocity, aircraft
V	number of non-coherent propagation paths
$\mathbf{v}$	three dimensional velocity vector
w	discrete waypoint out of a total of W waypoints in the <i>AERO-FS</i> interference model
W	total number of discrete W waypoints in the <i>AERO-FS</i> interference model
$x, \tilde{x}$	receive signals, wanted, unwanted
x_0	reference value for Kernel density estimation
$\mathbf{x}_i$	multidimensional data point in a data set $\mathcal{D}$
x, y, z	Cartesian coordinates
Y_{p}	polarization discrimination
Y_{L}	link degradation
$y, \tilde{y}$	receive signal, wanted, unwanted
z	assignment of a simulation sample l to a cluster center μ

List of acronyms

AC	aircraft
ADF	average duration of fades
A-ESIM	aeronautical-earth station in motion
AI	artificial intelligence
Art.	article
ASI	adjacent-satellite interference
BIC	Baysian Information Criterion
BNetzA	Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen
cdf	cumulative distribution function
CEPT ECC	Conférence Européenne des Administrations des Postes et des Télécommunications Electronic Communications Committee
CITEL	Inter-American Telecommunication Commission
CNPC	control and non-payload communication
co	coherent/specular
COTS	commercial of the shelf
CS	channel separation
ECEF	Earth-centered, Earth-fixed
ENU	East, North, Up
EIRP	equivalent isotropically radiated power
EIRP-SD	equivalent isotropically radiated power spectral-density
ERC	European Radiocommunications Committee
ESIM	earth station in motion
FBR	front-to-back-ratio
FCC	Federal Communications Comission
FDMA	frequency division multiple access
FOV	field of view
FPGA	Field Programmable Gate Array
FS	fixed service

FSMC	finite state Markov chain
FSS	fixed-satellite service
GMM	Gaussian Mixture Model
GPS	Global Positioning System
GSO	geostationary satellite orbit
H	horizontal
HMM	hidden Markov model
HOMP	higher order Markov process
HTS	high throughput satellite
I	in-phase
ISI	inter-symbol interference
ICAO	International Civil Aviation Organization
IF	intermediate frequency
IFE	in-flight entertainment
INR	interference-to-noise ratio
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union-Radiocommunication Sector
ITU-RR	Radio Regulations
KDE	kernel density estimation
L	linear
LB	link budget
LCR	level crossing rate
LEO	low Earth orbit
LHC	left hand circular
LN	log-normal
LNB	low noise block converter
LOS	line-of-sight
LSN	log-skew-normal
MEO	medium Earth orbit
MIFR	Master International Frequency Register

ML	machine learning
MPC	multipath component
MS	mobile service
MSE	mean squared error
MSS	mobile-satellite service
nco	non-coherent/diffuse
No.	Provision
NTN	non-terrestrial networks
OOB	out-of-band
pdf	probability density function
pfd	power flux-density
Pr	probability
psd	power spectral-density
Q	quadrature
Rec.	Recommendation
Rep.	Report
Res.	Resolution
Rev.	Revision
RF	radio frequency
RFI	radio frequency interference
RH	radio horizon
RHC	right hand circular
RoP	Rules of Procedure
SATCOM	satellite communication
SES	Société Européenne des Satellites
SDR	software defined radio
SN	skew-normal
SINR	signal-to-interference-plus-noise ratio
SNR	signal-to-noise ratio
UAS	unmanned aircraft systems
USB	Universal Serial Bus

V	vertical
Vol.	Volume
VQ	Vector-Quantization
WRC	World Radiocommunication Conference

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