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ASSESSMENT OF RADIO FREQUENCY INTERFERENCE RELEVANT TO THE GNSS L1 FREQUENCY BAND

RTCA DO-235C
March 17, 2022

Prepared by RTCA SC-159

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FOREWORD

This report was prepared by Special Committee 159 (RTCA SC-159) and approved by the RTCA Program Management Committee (PMC) on March 17, 2022.

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- coalescing aviation system user and provider technical requirements in a manner that helps government and industry meet their mutual objectives and responsibilities;
- analyzing and recommending solutions to the system technical issues that aviation faces as it continues to pursue increased safety, system capacity and efficiency;
- developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards for electronic systems and equipment that support aviation; and
- assisting in developing the appropriate technical material upon which positions for the International Civil Aviation Organization and the International Telecommunication Union and other appropriate international organizations can be based.

The organization's recommendations are often used as the basis for government and private sector decisions as well as the foundation for many Federal Aviation Administration Technical Standard Orders.

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EXECUTIVE SUMMARY

Background

Radionavigation systems used in aviation and other public safety applications must have reliable signals to function as intended. Certain commercial radio communication systems can afford some amount of degraded service due to interference, but safety-of-life systems cannot. What is at risk -- service on the one hand and loss of life on the other -- are fundamentally different, as are the ramifications of the occurrence of interference events to these different services. The issues surrounding potential interference to aeronautical systems cannot be taken lightly. These systems must be guarded from any interference that degrades their intended function.

The RTCA Task Force #1 Report on the Global Navigation Satellite System (GNSS) Transition and Implementation Strategy (September, 1992) recommended that RTCA develop standards to aid in operational certification of GNSS equipment. Since radio frequency interference (RFI) potentially degrades (GNSS) performance (accuracy, availability, continuity, and integrity), a careful and thorough examination of RFI was necessary.

The original RTCA assessment of GNSS RFI (RTCA DO-235, 1996) identified potential sources of RFI and assessed the vulnerability of GNSS receivers (particularly GPS) to that interference. The navigation signals considered were the GPS and GLONASS Standard Positioning Service (SPS) signals on their respective L1 carrier frequencies (1575.42 MHz for GPS), and the L1 signals transmitted by the FAA Wide Area Augmentation System (WAAS). Motivating factors for the original assessment included sporadic reports of GPS interference from various RFI sources, the potential RFI from new sources in adjacent frequency bands, and the need to identify appropriate mitigation measures for flight-critical GNSS applications. DO-235 findings aided development of early versions of the WAAS and LAAS (Local Area Augmentation System) MOPS and International Civil Aviation Organization (ICAO) Annex 10 GNSS SARPS (Standards and Recommended Practices). They were also used in International Telecommunication Union Radiocommunication Sector (ITU-R) Recommendation M.1477.

The first revision of DO-235 (DO-235A, December 2002) came from an RTCA investigation requested by the US Department of Transportation (DOT) in 1999 and augmented in 2000. The work was to assess the RFI environment for aviation use near the new GPS L5 frequency band (1176.45 ± 12 MHz) and augmented to include new potential RFI source (Ultra-Wideband (UWB) emissions) that could cover both the new L5 band and the GNSS L1 band (1559-1610 MHz) from DO-235. The assessment was to also include input from other non-aviation public safety applications. DO-235A set the framework for subsequent assessments, aided GNSS MOPS development in RTCA SC-159 and ICAO GNSS SARPS, and proved useful in guiding regulatory policy for UWB emissions. The L5 band work resulted in RTCA DO-292 (July, 2004).

The second revision (DO-235B, March 2008) was done to address several aspects: new operational scenarios with L1 band link analyses patterned after DO-292, explicit treatment of intra-system GPS and inter-system Galileo GNSS satellite signals from the latest signal standards, out-of-band pulsed RFI, on-board T-PEDS (transmitting portable electronic devices) and installed aeronautical equipment, and terrestrial non-aeronautical RFI from a collection of sources.

DO-235B findings have been widely accepted and incorporated into other domestic and international standards and recommendations. The receiver susceptibility recommendations are in upgrades to the RTCA DO-229() GPS/Satellite-Based Augmentation System (SBAS) MOPS and new standards for GPS/LAAS ground-based augmentation (GBAS) operation (DO-245() and DO-253()) and standalone GPS Sensors (RTCA DO-316). The (ICAO) Navigation Systems Panel has developed SBAS and GBAS Standards and Recommended Practices (SARPs) for international GNSS implementation with susceptibility requirements from DO-235B. DO-235B GNSS receiver susceptibility requirements have also been included in (ITU-R M.1903) and have also been the basis for adjacent band compatibility assessments seen in RTCA DO-327. In addition, the aeronautical community recommendations for MSS transmitter emission limits have been also incorporated into domestic and international standards and regulations.

Since the time of RTCA DO-235B's publication, several developments motivated an updated GNSS L1 RFI assessment. Aviation application factors included:

a. Ongoing activity to develop a dual-frequency, multi-constellation GNSS solution addressing GPS L1/L5 and Galileo E1/E5a.
b. The need for additional robustness to higher power adjacent band signals above GPS in the 1 616-1 626 MHz band (Iridium Certus).
c. Revision of the technical analyses of intersystem and intrasystem interference between GNSS signals.

In a wider view, GPS has become part of the critical infrastructure not only within the United States but also in other nations around the world. It is increasingly used by numerous commercial services and several non-aviation industries have been created by civil use of GPS. Such functions dependent upon GPS, which are critical to society, include banking transactions, power distribution, telecommunications timing, farming, general location and navigation and Enhanced 911 (E911). In addition, as the number of on orbit Galileo E1/E5a capable satellites increase, there are key efforts being undertaken to augment Galileo towards ensuring its applicability to airborne safety of life use.

This report updates the existing assessment of aeronautical GNSS RFI encounter scenarios and risk modeling, adds RFI effects assessment of dual-frequency, multi-constellation receivers to that of single frequency GPS L1 receivers, and includes the effects of an updated analytic statistical of terrestrial non-aeronautical RFI sources, increased GNSS intra- and inter-system RFI, increased onboard aeronautical equipment RFI and the effects of personal electronic devices carried on-board aircraft. The findings in this document DO-235C are anticipated to be reflected in future versions of the GNSS MOPS, including ED-259.

Terms of Reference and Report Objectives

RTCA SC-159 WG6 was created to investigate radio-frequency interference issues, and appropriate mitigation alternatives, relevant to GNSS. The original and subsequent Terms of Reference for this group that are still applicable are:

1. Develop quantitative assessments of the current and projected RF interference (RFI) environment;
2. Recommend measures to reduce RFI at the source where it is technically feasible and cost-effective to do so;
3. Develop updated interference rejection criteria for future GNSS receivers that will enable them to satisfy required navigation performance in the near future RFI environment;
4. Develop RFI encounter scenarios for new aeronautical operations with GNSS receivers, review and revise current scenarios as required;
5. Update, as required, the assessment of existing and new L1 RFI sources, the existing GNSS receiver susceptibility standards, and other RFI mitigation means to aid evolving aeronautical GNSS development.

In October 2016, RTCA SC-159 approved the task of updating the DO-235B report to:

a. Revise the link analyses in line with the latest GPS L1 C/A signal specification (IS-GPS 200()) and Galileo E1 OS signal in space (OS SIS ICD Issue()) specification;

b. Improve aggregate terrestrial RFI modeling to refine non-aeronautical emitter impacts to safety of life use of the GPS and Galileo L1/E1 signals;

c. Revise the analysis and link margin implications of GNSS intersystem and intrasystem interference based on the updated GNSS sensor and SiS assumptions supported by recent advances in GNSS intersystem and intrasystem interference modeling.

d. Concern about the performance of both the GPS/Galileo L1/E1 band dual-frequency receivers and the legacy GPS L1 band single-frequency receivers in an increased RFI environment and appropriate receiver test conditions to represent the environment.

e. Address changes to on board aeronautical RFI environment that could impact L1 GNSS operations.

f. Update the in band and adjacent band RFI Mask in support of developing resilient safety of life airborne GNSS (GPS/Galileo) receiver solutions.

Report Structure and Content

The report is organized into fifteen sections with supporting material in thirteen appendices. Contents of the report body are summarized as follows:

Section 1 - Introduction

Section 2 - Groundwork for the assessment of GNSS receiver RFI susceptibility in terms of basic system performance requirements, the source-path-receiver RFI link analysis technique, receiver susceptibility limits and other general factors in the RFI link.

Section 3 - RFI encounter scenarios for aeronautical GNSS operations: enroute acquisition, high altitude enroute navigation, terminal area navigation, non-precision approach, Category I precision approach, and Category II/III precision approach.

Section 4 - Non-aeronautical RFI scenarios developed by outside experts: GPS-aided Enhanced-911 automatic mobile phone position reporting, high-accuracy maritime navigation; and airport survey (retained unchanged from the previous report).

Sections 5 through 12 address interference from various classes or types of intentional, unintentional, and incidental RF emitters. These include:

- Section 5 - Mobile Satellite Service (MSS) and Ancillary Terrestrial Component (ATC) emitters
- Section 6 - Onboard Emitters
- Section 7 - Fixed Aeronautical Emitters
- Section 8 - RFI Sources on Nearby Aircraft
- Section 9 - Commercial Broadcast Services
- Section 10 - Other Ground-based Services
- Section 11 - GNSS intrasystem and intersystem interference (i.e.; from GPS, Galileo, QZSS, BeiDou and SBAS satellite signals) to L1 C/A code and Galileo E1 OS receivers.
- Section 12 – Unintentional, Incidental Ground-based Emitters

Section 13 – Formulation of total non-aeronautical and aeronautical RFI values for the RFI scenarios and RFI link analyses for the various GNSS enroute and approach RFI scenarios for GPS and Galileo receivers.

Section 14 - Mitigation methods (source-related, receiver-related, operational) appropriate for significant RFI sources;

Section 15 - Status of the original report recommendations, summary of the current report, and new recommendations.

The thirteen Appendices cover a variety of subjects that support and expand on the areas covered in the main body. Appendix A (precision approach TSE statistics), Appendix B (RFI source specifications), and Appendix C (GPS L1 C/A code signal structure and effects on other C/A code signals) are updated slightly from the previous L1 report versions. Legacy material in Appendix D (analytical derivation of receiver signal-to-noise density thresholds and saturating pulse effects) is updated with details on Galileo E1 OS acquisition and tracking. Relevant Appendix E (receiver RFI performance emulation and simulation) legacy material has been retained and new material on GNSS intrasystem and intersystem RFI (representative satellite constellation parameters) is added. Appendix F (standard received signal and interference environment) shows the updated GNSS RFI mask for DFMC receivers and has details on the GNSS test noise conditions and related test procedure recommendations. Appendix G (Installed Aircraft GNSS Antenna Performance Model) has RTCA DO-301 active antenna MOPS material and scale model aircraft installed pattern measurements and simulation. Appendix H (Effects of UWB Interference Signals on GPS Receivers) legacy material has been retained. Legacy material has been retained in Appendix I (Line-of-Sight Propagation from Multiple RFI Sources) and substantial new material on analytical statistical terrestrial RFI modeling has been added. Appendix J (Take-off, Missed Approach, and Surface Movement Scenarios) has supplemental material for RTCA DO-292 scenarios not treated in the main body. Appendix K (GPS Receiver UWB Susceptibility Tests and Analysis) is retained unchanged from the previous DO-235 report for historical reference purposes. Appendix L now has the UWB information that used to reside in the main body of the previous version of the DO-235 document.

Appendix M provides the background on the US L Band MSS/ATC authorization. Appendix N (Acronyms, Abbreviations, and Definitions) has been updated from the previous report.

Report Summary and Conclusions

Summary Overview

This report examined potential sources of interference and assessed the susceptibility of GNSS receivers to that interference. Potentially significant sources of interference exist on aircraft as well as on the ground. In the absence of specific mitigation techniques, GNSS appear to be at risk of degradation due to interference from licensed sources, as well as unlicensed or malfunctioning electrical equipment. Potential sources of interference include UWB transmitters, portable electronic devices used on the ground and carried on-board aircraft, ground based VHF and UHF transceivers, and unwanted emissions from adjacent frequency band communications satellites and their associated ground-based user equipment.

This report has proposed an analytic statistical aggregate RFI effect model for a distribution of non-aeronautical terrestrial RFI sources out to the aircraft antenna radio horizon. That model was used to estimate a mean aggregate source RFI emission power statistics in the L1 band that would be compatible with GNSS operations, particularly precision approach.

U.S. rules for regulating the use of UWB technology were established several years ago. These rules were intended to protect GNSS operations among others. UWB capable consumer and commercial devices are now available for purchase. UWB waivers will need to be monitored to ensure the continued protection of GNSS equipment.

The FAA through emission limits and installation practices has effectively dealt with interference from VHF transceivers employed for air-ground communications for both air carrier and general aviation aircraft. Updated standards have been developed and put into a regulatory framework. Although no significant incidence of RFI has been observed to date, VHF transceivers on the ground continue to be potential sources of interference. They may be associated with aviation as well as non-aviation equipment and may be fixed or mobile. Aviation equipment may be used by ground operations personnel in close proximity to aircraft on the ground or on final approach. VHF equipment is ubiquitous in land-, sea-, and airborne mobile operations.

GNSS intrasystem and intersystem RFI effects have been investigated in detail for this report. The investigation explicitly addressed the impact of inter and intra-system interference for a GNSS receiver tracking the GPS L1 C/A signal in the presence of new signals (such as GPS L1C) and includes the impacts due to the expanded set of SBAS PRN's (120-158) and other RNSS systems such as QZSS and Galileo. In addition, the assessment also reflected the impacts of intersystem and intrasystem interference for a GNSS receiver tracking the Galileo E1B/C signal in the presence of signals from other RNSS constellations that are centered at 1 575.42 MHz in the GNSS L1 band.

GNSS may be at some limited risk of degradation due to interference from other sources (e.g., fixed service, broadcast services, radar, and experimental systems).

However, these potential sources of interference are limited in number, and may be more easily controlled than the mobile sources of interference, or unlicensed and malfunctioning equipment. The FAA has instituted a structured program to control potential sources of interference to GPS and WAAS.

With respect to broadcast television, the FAA and the FCC have come to agreement on emission limits for digital TV broadcasts that will protect GPS L1 airborne operations. With respect to MSS, US domestic and international regulations have set a -70 dBW/MHz MET emission limit in the frequency band 1 559-1 605 MHz for broadband emissions.

The Fixed Service no longer has an allocation in the 1559-1610 MHz frequency band. International Radio Regulation footnotes that had permitted the allocation in certain countries were suppressed at the 2015 World Radiocommunication Conference (WRC-15).

Additional and unexpected sources of RF interference are of concern for all radionavigation systems. The potential for RFI from the combination of unexpected aggregate interference from new or existing sources such as VHF transceivers, and unpredictable interference from unlicensed (e.g., UWB) or malfunctioning or inadvertently-operated equipment, highlights the need for continuous vigilance.

New National Space Policy Directives lay out the framework for multi-government agencies and commercial stakeholders to combine and collaborate on detection and characterization of interference to GPS serving critical infrastructure (CI) sectors with comprehensive strategic guidance, roles and responsibilities. This new Space Policy Directive (SPD7) includes all CI sectors using GPS and any other Position Navigation and (PNT) Timing service delivery system that could be experiencing RF interference disruptions. Enforcement and regulatory compliance processes have been strengthened to allow rapid negation of the interference once it has been identified and localized. Key RFI link analysis findings are discussed later in this summary.

Aeronautical Navigation System Requirements and Analysis Methodology

Aeronautical system risk analysis assigns loss-of-continuity and loss-of-integrity probabilities to the navigation system necessary to ensure safety in various phases of flight. The navigation system performance budget allocates loss-of-continuity and loss-of-integrity probabilities to elements of the navigation system (e.g., airborne navigation receiver, signal-in-space, ground equipment, etc.). System analysis also results in accuracy allotments of the Total System Error (a combination of Navigation System Error and Flight Technical Error). Those allocations become part of the detailed performance requirements for the system element.

GBAS and SBAS MOPS-compliant receivers must satisfy certain performance parameter requirements (e.g., pseudorange error, SBAS message error rate, satellite acquisition time) in the presence of a specified set of RFI test conditions that represent aeronautical and non-aeronautical components of the RFI environment. The adequacy of the RFI test conditions and feasibility of achieving acceptable receiver performance is assessed through RFI link analyses.

The RFI link analyses use the source-path-receiver method. The receiver interference link performance is based on comparing the carrier-to-effective noise density ratio, $C/N_{0,EFF}$, with the minimum receiver signal processing threshold derived for the particular performance requirement. The $C/N_{0,EFF}$ signal, noise, and RFI components are computed from various specifications, "minimum-performance" receiver model parameters, and estimates of the aggregate RFI from various source categories. The receive antenna gain model is an important aspect in the received signal and aggregate RFI computations. One difference with previous assessments is the assumed presence of a distribution of terrestrial non-aeronautical RFI sources out to the radio horizon for the aircraft GNSS antenna. The RFI effect of a nearby MSS MET is implicitly included in the aggregate non-aeronautical RFI for precision approach link analysis.

Because GNSS used for aeronautical radionavigation performs a safety-of-life function, an aeronautical safety margin of 6 dB is used to explicitly account for uncertainties in non-aeronautical RFI components. The margin is applied as a multiplier to the estimated aggregate non-aeronautical RFI level before it is inserted in the $C/N_{0,EFF}$ equation. This magnified RFI value also serves as the non-aeronautical RFI test condition in the GNSS receiver MOPS.

Aeronautical RFI Encounter Scenario Descriptions

Scenarios from the previous RTCA DO-235B report were reviewed for potential updates. In most cases aircraft Total System Error statistics were derived and applied to determine the probability the aircraft and RFI source would not be closer than the stated minimum separation distance. The Enroute/Terminal Area Navigation scenario now has a smaller RFI separation distance to cover certain terminal area operations. The Non-Precision Approach scenario has a smaller separation distance and new associated probabilities (dependent on aircraft receiver equipage). The minimum separation distance for Category I Precision Approach remains the same. The scenario parameters for separation distance, associated probability, and antenna gain toward the RFI source are summarized below (Table EX-1). These parameters for the propagation path were used in the subsequent link analyses for significant RFI sources.

Table EX-1: Aeronautical RFI Encounter Scenario Parameters

Scenario	Obstacle Separation Dist. (feet)	Ant. Height (feet)	Probability of smaller distance	Rcv Ant. Gain (RFI)	Comments
Enroute/ Terminal Area	500 (min)	18 000 / 1 756	N/A	Use Cat I Model	Operation in some regions results in 1000' min. separation
Non-Precision	100	various	$5.\ 2\times10^{-3}$ (-208) 1.6×10^{-3} (-229F)	Use Cat I Model	RTCA DO-229 receiver has lower NSE than RTCA DO-208
Category I	96.7	175	$< 1\times10^{-6}$ auto $2.8\text{x}10^{-4}$ manual	Cat. I Model	
Category II/III	70	85.1	1×10^{-7}	Cat II Model	

Non-Aeronautical RFI Encounter Scenario Development and Analysis

The GPS Industry Council provided scenario information for GPS-aided E-911 position reporting and performed RFI link analysis for UWB RFI to GPS E-911 cellular telephones. The US Coast Guard provided high-accuracy maritime navigation scenarios and UWB RFI link analyses. The National Geodetic Survey provided information on an Airport Survey scenario and investigated VHF transmitter harmonic RFI to GPS L1/L2 semi-codeless receivers. These non-aeronautical scenarios from RTCA DO-235B are retained unchanged in this new assessment report. No new material was submitted to update them.

GPS-Aided Enhanced-911 Cellular Telephone Position Reporting

E911 deployment relies heavily on GPS for position reporting. Furthermore, building attenuation for indoor use and urban canyon and foliage attenuation outdoors reduce GPS signal levels and increase RFI susceptibility. UWB devices for wireless local area networks have already been authorized for indoor operation. According to the RFI link analysis in this report, indoor device EIRP must be kept below –114 dBW/MHz (noise-like emission) to avoid excessive RFI to indoor E-911 GPS. Outdoor UWB device EIRP must be kept below –108 dBW/MHz for compatibility with outdoor E-911 GPS.

Maritime

Maritime GPS performance is most critical in docking and lock operations, and in constricted waterways (the two scenarios developed for this report). Unfortunately, in these scenarios, the maritime GPS receiver has the closest spacing (30 feet) to mobile RFI sources (e.g., UWB). Dynamic RFI link analysis shows that a source with –83 dBW EIRP in the GNSS L1 band produces a received

RFI level exceeding the maritime receiver tolerance threshold (and thus a performance outage) for a duration of between 10 and 110 seconds. An outage duration longer than 10 seconds could significantly impact these vessel operations.

Survey

The NOAA National Geodetic Survey (NGS) in support of the FAA is working with private survey organizations to perform highly accurate aeronautical surveys at public use airports. NGS field survey crews have experienced GPS interference while conducting kinematic runway profiles and transmitting (for surface movement coordination) on the Air Traffic Control VHF band. A survey scenario was developed to aid the analysis. When the dual-frequency GPS survey receiver loses carrier phase tracking continuity on multiple satellites, the survey is terminated, and re-initialization is required. Harmonic RFI from the mobile VHF transceiver on the survey vehicle (4-foot antenna separation to the GPS antenna) was the suspected cause. The actual mechanism was determined to be harmonic RFI at the GPS L2 frequency. Another source of RFI was encountered during survey work at Logan Airport, Boston MA. There the suspected cause was harmonic emission from an FAA communications transmitter.

RFI Source Assessment Summaries

Mobile Satellite Service Emitters

This report section addresses four non-aeronautical Mobile Satellite Services (MSS) physical components. The space components are systems of low Earth orbit satellites (LEOs) and Geosynchronous (GSO) satellites; the earth-based components are fixed gateway (or ground earth) stations and subscriber portable (handheld) devices. The latter are termed MSS Mobile Earth Transmitters (METs). Four types of potential MSS RFI source emissions are earth-to-space broadband (noise), earth-to-space narrowband (CW), space-to-earth broadband and space-to-earth narrowband. MSS MET unwanted emission limits derived in a previous assessment are now in FCC regulations. Previously derived MSS satellite out-of-band aggregate emission limits in the GNSS L1 band (-147.7 dBW/MHz/m^2 broadband and -157.7 dBW/m^2 narrowband) are still proposed as single-entry values in coordination. MSS Ancillary Terrestrial Component operation (terrestrial tower base stations performing the function of the MSS satellites) was addressed. Mobile user terminal regulatory emission limits are the same as the mobile satellite (MET) units, but service providers have agreed to tighter limits for compatibility with GPS.

Interference from Onboard Electronics

Interference to GNSS from onboard installed electronics equipment has been under investigation for several years by RTCA and the FAA. Installed equipment such as VHF transceivers, ATCRBS and DME beacons have been largely dealt with and mitigation techniques are well in hand. An investigation for this assessment report to validate a proposed reduction in a GNSS MOPS pulsed RFI test condition concluded that the onboard pulsed L-band transmitter saturating-pulse composite duty cycle was 0.85% (worst case), This worst-case composite together with a 0.15% duty cycle allowance for off-board radars make up the 1% duty cycle saturating pulsed RFI test condition.

An update to the onboard RFI source was identified in this assessment – installed cockpit equipment unintentional case radiation. The aggregate case radiated RFI density level estimated for an equivalent of 12 sources equals 18% of the system thermal noise. More effort may be needed to verify that estimate and improve RTCA DO-160 test limits and procedures (as needed).

The potential for interference from portable electronic devices (PEDs) carried aboard by passengers is increasing due to the rapid growth in PED popularity and use. Further studies are needed to better quantify the emission characteristics and radiation pattern of representative devices. That information is needed to more accurately model the aggregate effects and develop appropriate mitigations.

Fixed Aeronautical Emitters

While several cases of GNSS interference caused by on-board VHF transmitters have been found, RFI reports based on fixed ground-based VHF transceivers are rare. To protect GNSS receivers from ground-based VHF transceivers, a separation distance greater that the Category I minimum vertical separation (Chapter 3) is required. No problems of GNSS interference from VOR harmonics have been reported to date. The combined influence of several factors makes DME ground station RFI negligible. Careful GBAS ground station site engineering is needed to mitigate RFI from the 1-1.7 GHz band unwanted emissions of VHF Data Broadcast transmitters. Airport pseudolites would require careful design to avoid interference to normal GNSS L1 signal reception but are no longer being planned for use in the FAA aeronautical GNSS ground infrastructure.

Interference from Avionics on Nearby Aircraft

Minimum allowable airborne separation distances are sufficient to reduce interference to GNSS L1 to insignificant amounts. The closer proximity of adjacent aircraft on the airport surface (e.g., in sequence on a taxiway) could potentially result, however, in RFI from systems on some aircraft to GNSS L1 equipment on others. Five potential interference sources were assessed: VHF transceivers, DME interrogators, military JTIDS/MIDS terminals, Aeronautical Mobile- and generic Mobile Satellite Service transmitters. VHF transmitter RFI is the most troublesome especially when it has not been mitigated to allow onboard GNSS use. The calculated separation distance (210 feet) may require consideration in the future deployment of GNSS-aided surface movement.

Commercial Broadcast Service Emitters

AM, FM radio broadcast transmitter high-order harmonic emissions fall close enough in frequency to GNSS L1 to potentially cause interference. With AM broadcast, however, the harmonic order is so high (~985) that the likelihood of RFI is considered minimal. For FM broadcast the harmonic order is lower (15 to 18) and the maximum EIRP is higher (50 to 60 dBW). Given the minimum required transmitter harmonic rejection, the theoretical separation radius for tolerable RFI to a GNSS L1 receiver is at least 10 miles. However, no cases of FM broadcast RFI to GNSS have been documented.

Analog TV broadcast maximum EIRP limits are higher than FM and harmonic orders are lower (2 to 9 for RFI signals within 2 MHz of GPS L1) and predicted minimum separation radii exceeded 100 miles. The worst cases are the Channel 23 picture carrier (3rd harmonic) and the Channel 66 sound carrier (2nd harmonic) which fall within 0.33 MHz and 0.08 MHz, respectively, of GPS/Galileo L1. Field measurements of harmonic levels have shown, however, that TV harmonic suppression is actually more than 40 dB greater that the minimum 60 dBc requirement. Digital TV RFI to GNSS (assessed in an earlier revision of this report) is also shown not to be significant due to engineering, regulatory, and frequency management factors.

Given the above indicated field data for analog TV harmonic suppression and the steady move towards digital TV, Analog TV RFI to GNSS is therefore not considered to be a problem. Analog TV is being replaced with digital TV in many parts of the work and the trend towards analog TV is to limit it to low power for local use.

Other Fixed and Mobile Interference Sources

The number of RFI sources in the category assessed in this report increased significantly from the original report as a reflection of the significant growth of wireless equipment types. One area of concern is the reallocation of certain high UHF TV channels for Public Safety wireless communications. Second harmonic emissions would fall on or near GNSS L1 and the emission limit is under consideration. Some of the devices in the category must meet 47 CFR Part 15 spurious emission limits, but that limit allows almost as much spurious power as an MSS MET is permitted to radiate in the GNSS L1 band. Others have higher spurious limits approaching –43 dBW. Discussion of the current status of ultra-wideband transmission systems was condensed from the RTCA DO-235B report and moved into the Appendices for reference. Discussion on GPS re-radiators was added and the actual RFI effect was determined to be like multipath interference. In spite of the potential, no known cases of GNSS L1 RFI have been reported for devices in this general category. GPS re-radiators warrant special attention, however, and should not be sited near airport runway approaches.

GNSS Intrasystem and Intersystem Interference

A detailed methodology for analyzing GNSS intrasystem and intersystem interference is developed in this report. The analysis has shown that the most significant source of self-interference to C/A code is other C/A code signals. In the case of C/A code signals interfering with a desired C/A code signal, the power spectral density varies with Doppler differences between satellite pairs. The resulting GNSS noise density conditions that are seen in Table F-6. The assessment of GNSS noise densities to Galileo E1 OS is based on the long code approximation and the respective limiting GNSS test noise conditions that are recommended for the purposes of testing are seen in Table F-7.

Additional Interference Sources

The additional sources of interference assessed in this report include the general groups of unintentional and incidental emitters and malfunctioning RF equipment and inadvertent transmitter operation. Unintentional RFI sources intentionally generate RF signals for internal use but do not intentionally radiate them (e.g., computers, radio receivers). Incidental RFI sources generate RF energy incidentally in the course of operation but they are not designed specifically to generate or emit RF (e.g., amplifiers, DC motors, and arc welders). These types of sources have caused interference to other important radio communication navigation services before but there are few reported cases of interference from this category to GNSS. Malfunctioning RF equipment emission and inadvertent transmitter operation have caused more problems for GNSS in recent times. The main strategies to deal with RFI from these sources involve RFI environment monitoring and direction finding to isolate the source. Inadvertent operation is best avoided by transmitter operator education. Prompt reporting of RFI incidents by GNSS users and quick, efficient follow-up by cognizant agencies are important mitigation aspects for all these categories

GNSS Enroute and Approach RFI Link Analyses Summary

Using the basic RFI modeling approach, scenario geometry, and RFI source category descriptions, this report section develops RFI link analyses for six RFI encounter scenarios. Those scenarios are Category I and II/III precision approach, non-precision approach, terminal area (Cat. I FAF waypoint), enroute acquisition (GPS, Galileo) and signal tracking (GPS, Galileo and SBAS L1). The main analysis objectives were to assess the RFI compatibility of GPS/Galileo L1/E1 OS receivers in these key operations and the adequacy of receiver MOPS RFI test conditions to represent the RFI environment.

Composite Aeronautical Continuous RFI

Scenario-dependent composite aeronautical RFI values were developed in which the refined GNSS satellite signal self-noise RFI was combined with an aggregate on-board cockpit equipment case-radiated RFI and (for certain scenarios) a continuous on-board antenna radiated RFI component. Tables F-6 and F-7 provide the details on the Effective GNSS Noise densities for worldwide GPS L1 C/A and E1 OS components of the DFMC GNSS receiver operations. In addition, given the approach espoused in this analysis to address the L1 C/A GNSS self-interference, guidance on specific test conditions and procedures to help evaluate receiver performance under these limiting interference conditions are provided in Appendix F.2.3.3. Note that L1/L5 sensors are paired with an L1/L5 antenna and L1 sensors are paired with an L1 antenna.

Composite Non-Aeronautical Continuous RFI

The aggregate on-board non-aeronautical RFI from PEDs was estimated from NASA device emission and aircraft coupling path loss measurement data at about -152.5 dBW/MHz. With 6 dB safety margin added, this component equals the present RTCA DO-229F MOPS enroute RFI test condition and leaves no allowance for any aggregate ground RFI component. Additional detailed emission testing and analysis is needed to determine and separate noise-like and discrete emission features in the GNSS L1 band for the key device types. More study is also needed on the aggregation mechanism.

Ground-based non-aeronautical aggregate continuous RFI has been modeled for this assessment with an analytic statistical method developed under FAA contract in response to a DO-235B recommendation. The results indicate that received aggregate mean values are well below the -146.5 dBW/MHz mean value limit associated with the precision approach receiver MOPS test condition (-140.5 dBW/MHz -6 dB safety margin). Also for aircraft altitudes at or above 1 000 feet (304.8 m) above ground level, statistical analysis results indicate the probability of the aggregate non-aeronautical ground-based RFI exceeding -143.5 dBW/MHz is less than 5x10-8. Thus for link analyses of aircraft operations at or above 1 000 feet AGL, the non-aeronautical aggregate RFI psd is set at -143.5 dBW/MHz and for operations below 1 000 feet (e.g. precision approach), the aggregate RFI is -140.5 dBW/MHz as in the DO-235B recommendation.

RFI Link Analyses Results Summary

Given a 24 SV (satellite vehicle) GPS constellation with 2 SV's unhealthy, dual-frequency GPS L1 precision approach link analysis results in the Asia-Pacific area show that under worldwide limiting-case composite aeronautical and non-aeronautical RFI and minimum GPS signal conditions, the "minimum performance dual-frequency receiver model" tracking performance has slightly negative link margin. This analysis result should be verified by receiver tests. However for high-altitude L1 RFI test conditions, the dual-frequency GPS receiver model has positive link margins for signal tracking and acquisition in the Asia-Pacific region. A dual-frequency, minimum performance model Galileo E1 OS receiver under the worldwide limiting-case composite RFI and minimum E1 signal conditions has positive link margin for precision approach. Enroute and high-latitude SBAS-aided approach L1/E1 band links for both dual-frequency GPS and Galileo model receivers have larger positive link margins.

The legacy single-frequency GPS L1 C/A receiver system model is still compatible with current estimated higher RFI environment for precision approach at the domestic limiting-case US locations used in DO-235B as long as the lowest elevation GPS satellite needed for GBAS or SBAS precision approach integrity is above about 9°. Given the domestic US results, the further increased aeronautical RFI environment in the Asia-Pacific area (~100° E-175° E long.) is problematic for precision approach with the legacy single-frequency model. Legacy GPS receiver model link margin issues are resolved with a 30 SV constellation and for operational altitudes above 1 000 feet AGL with a depleted 24 SV constellation.

Based on an extension of the GBAS (LAAS) Category I approach link to the Category II DH scenario, the MOPS precision approach RFI test condition is found to be also applicable for Category II/III GNSS L1 precision approach conditions. The only additional constraint is that the GNSS antenna needs to provide 3 dB lower installed pattern gain in the lower hemisphere out 45º from nadir (-13 dBi vs. -10 dBi for Cat. I installations). It should be noted that the predicted probability that the non-aeronautical terrestrial RFI exceeds the -140.5 dBW/MHz (-170.5 dBm/Hz) MOPS test value is rather high for the Category II case and there may be a continuity impact. This prediction should be validated as requested in the previous assessment (DO-235B, recommendation #8).

Link analyses for the RFI encounter scenarios at higher altitudes than precision approach all show the effect of a rather slow decrease in estimated terrestrial non-aeronautical aggregate RFI with increasing aircraft height above ground. The links show positive margins with the applicable MOPS RFI test conditions which adequately reflect the non-aeronautical RFI, and still preserve a 6 dB safety margin. The non-aeronautical (external) RFI composite values for proposed future MOPS test conditions are:

- Signal tracking / reacquisition (precision approach)- remain at -140.5 dBW/MHz and apply to all GNSS operations (including NPA) up to 2 500 feet AGL (for MOPS tests);
- Signal tracking / acquisition (enroute, warm start) - remain at -143.5 dBW/MHz and apply to all operations above 2 500 feet AGL (receiver MOPS tests) and certain operational performance analyses may use -143.5 dBW/MHz at or above 1 000 feet AGL as appropriate;
- On-ground acquisition – remain at -146.5 dBW/MHz.

Sets of scenario-dependent composite continuous aeronautical RFI test conditions have been developed to be the replacement for the previously introduced "GNSS self-noise" test condition in the L1 receiver MOPS. These values are to simulate satellite signal and environment noise-like RFI in the test set-up not delivered by the GNSS satellite signal generator itself. Details are given in Appendix F.

Mitigation Techniques for Significant RFI Sources

This chapter addresses four areas in which mitigation techniques can be applied: control / elimination of interference at its source, reduction of GNSS receiver susceptibility to interference, reduction of overall navigation system susceptibility to GNSS interference, and imposition of operational constraints. Progress has been made in the area of RFI source control both in regulatory aspects for certain sources and in monitoring and direction finding capability. The status for receiver susceptibility reduction techniques remains about the same as for the previous report –practical methods are being employed. Some developments in navigation system susceptibility reduction (tightly coupled inertials) have been deployed but more work is needed to better leverage these capabilities to address the threats of intentional and unintentional RFI. Further developments include the use of a second frequency (GPS L5).

Summary of Recommendations

The following is a brief overview of the recommendations made based on the activities outlined in this document.

1. Certification criteria for GPS disruption to be reviewed given the SBAS MOPS and lack of requirement to meet RTCA DO-160 limits.

2. Gather more detailed portable electronic device emissions test data in order to better model emissions for future GNSS susceptibility analyses.

3. Adoption of new RFI test conditions into the DFMC MOPS which were assessed as part of this work based on global RNSS constellations.

4. Verify further by test the FAA analytic statistical RFI evaluation theory L1 band predictions with testing and extend it to cover the L5 frequency band.

5. External RFI MOPS test conditions should be revised to better account for aggregate effects of terrestrial RFI sources and of on-board PEDs.

6. Forbid fixed GNSS re-radiators from being located near airport runway approaches.

7. Creation of an actionable framework to help protect airborne safety of life GNSS users through better detection, characterization, localization and neutralization of external interference sources.

8. Conduct a study to determine the RFI power limits that should apply to wider bandwidth RFI as a function of bandwidth for center frequencies outside 1 565.42 – 1585.42 MHz.

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1 INTRODUCTION

1.1 Background

The RTCA Task Force #1 Report on the Global Navigation Satellite System (GNSS) Transition and Implementation Strategy (September 1992) recommended that "the FAA should base GNSS initial operational implementation on the use of the U.S. GPS (Global Positioning System) national resource and appropriate augmentations". The Task Force also recommended that RTCA develop initial standards that will be used to certify GNSS equipment for operational use. The accuracy, integrity, availability and continuity of satellite-based navigation must be assured before it can be adopted into safety of life aviation use. Radio frequency interference (RFI) is a factor that potentially degrades system performance and one that must be examined with care.

RTCA SC-159 Working Group 6 was created to investigate radio-frequency interference issues, and appropriate mitigation alternatives, relevant to GNSS. The original Terms of Reference for this group were to:

1. Develop quantitative assessments of the current and projected RF interference (RFI) environment
2. Recommend measures to reduce RFI at the source where it is technically feasible and cost-effective to do so
3. Develop updated interference rejection criteria for future GNSS receivers that will enable them to satisfy required navigation performance in the near future RFI environment
4. Develop an out-of-band emissions mask for adjacent-band Mobile Satellite System mobile Earth terminals

The original GNSS L1 RFI environment assessment by RTCA (RTCA DO-235), completed in late 1996, identified potential sources of RFI and assessed the vulnerability of GNSS receivers (particularly GPS) to that interference. The original assessment was motivated by a number of factors. These included sporadic GPS interference trouble reports from various RFI sources, the potential RFI from new sources in adjacent frequency bands, and the need to identify appropriate mitigation measures for flight-critical GNSS applications. Out of the original assessment work came susceptibility requirements for RTCA DO-229 GPS/SBAS airborne receiver standard, two proposals for "Big-LEO" Mobile Satellite Service transmitter emission requirements, and several other key findings.

In October 1999 at Department of Transport (DOT) request, the RTCA undertook to investigate the RFI environment near the GPS L5 frequency (1176.45 ± 12 MHz) and determine appropriate receiver susceptibility criteria and related RFI unwanted emission limits for the use with new civil signal. Aviation-related issues were acknowledged to be of primary importance, but the group was to seek significant involvement and input from non-aviation public safety applications (e.g., maritime, E-911, police, fire fighting). By June 2000 the regulatory and business activity pace had intensified on ultra-wideband (UWB) transmission technology. As a result, the DOT requested the RTCA enlarge the study to explicitly treat UWB RFI effects and operational scenarios for the GPS L1 frequency as well as L5.

Additional terms were added in mid-2000 to address certain issues with UWB and other new RFI sources and proposed new operational uses. They were:

