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

RTCA/DO-235B

Supersedes DO-235A  
March 13, 2008

Prepared by RTCA SC-159

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## FOREWARD

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## EXECUTIVE SUMMARY

### Background

Radio navigation 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) 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 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 WAAS satellite-based augmentation system (SBAS) and new standards for GPS/LAAS ground-based augmentation (GBAS) operation (DO-245 and DO-253). The International Civil Aviation Organization (ICAO) GNSS Panel has developed SBAS and GBAS Standards and Recommended Practices (SARPs) for international GNSS implementation with susceptibility requirements from DO-235. DO-235 GNSS receiver susceptibility requirements have also been included in a new International Telecommunication Union Recommendation (ITU-R M.1477). The aeronautical community recommendations for MSS transmitter emission limits have been also incorporated into domestic and international standards and regulations.

Several developments between 1996 and 2000 motivated an updated GNSS L1 RFI assessment. Aviation application factors included:

- a. A Minimum Avionics System Performance Specification (MASPS) for Category II and III precision approach had been developed but the original DO-235 Category II/III RFI link budget had not been updated;
- b. New RF systems, most notably ultra-wideband (UWB) transmission systems, had arisen with potential interference consequences for GPS and the regulatory activity pace had intensified.

In a wider view, GPS was becoming part of the critical infrastructure not only within the United States but also in other nations around the world. It was 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, and Enhanced 911 (E911).

As a result of these factors the US Department of Transportation (DOT) requested the RTCA enlarge an RFI assessment effort already underway on the GPS L5 band (1176.45 ± 12 MHz) to explicitly treat UWB RFI effects and operational scenarios for the GNSS L1 frequency band. Aviation-related issues were acknowledged to be of primary importance, but the RTCA was to seek significant involvement and input from non-aviation public safety applications (e.g., maritime, E-911, police, fire fighting). RTCA produced two principal interim L1 band reports for DOT and a final report published in late 2002 as RTCA/DO-235A. In addition to a significant focus on UWB RFI, that report updated aeronautical GPS RFI encounter scenarios and risk modeling, and initiated assessment of Category II/III precision approach scenarios and the effects of personal electronic devices carried on-board aircraft. It also evaluated GPS intrasystem interference from C/A, Y and M code satellite signals by using the concepts of spectral separation and “critical” satellites.

After completing the GNSS L1 band update, RTCA resumed work on the GPS L5 band study and published RTCA/DO-292 in mid-2004. One significant aspect of that report to the present work is that it analyzed several encounter scenarios that were in addition to those analyzed for L1 in RTCA/DO-235A. Other important aspects are that it proposed computational methods for treating composite pulse and continuous RFI ( $C/N_{0,EFF}$  method) and for aggregate terrestrial RFI (both pulsed and continuous). These methods were further refined and used in the present report. The DO-292 report also showed that an L5 receiver with modest technology can perform properly in the presence of the most intense in-band and near-band pulsed RFI encountered in the US and Europe.

### **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 GPS receivers, review and revise current scenarios as required;
5. Update, as required, the assessment of existing and new L1 RFI sources, the existing GPS receiver susceptibility standards, and other RFI mitigation means to aid evolving aeronautical GNSS development.

In October 2004, RTCA SC-159 approved two new tasks:

6. Update the RTCA/DO-235A L1 band RFI assessment (primary activity) to include:
  - a. New operational scenarios patterned after RTCA/DO-292 with link analyses;
  - b. Link analyses revised for the latest GPS L1 signal specification (IS-GPS 200D) and Galileo L1 signal RFI effects;
  - c. Improved aggregate terrestrial RFI modeling to address unlicensed emitter proliferation;
  - d. Updated out-of-band pulsed RFI environment effects on GNSS L1 receivers;
  - e. Effects from new RFI sources such as on-board transmitting portable electronic devices (T-PEDs) and GPS re-radiators.
7. Coordinate as needed with other RTCA SC-159 Working Groups, RTCA SC-202 (T-PEDs), and Eurocae WG 62 (Galileo). (Secondary activity)

This report addresses the two newest activities as described in the new terms of reference above adopted in October 2004 by the RTCA Special Committee 159. One of the major outcomes of this report is the work done on development of a methodology to analyze aggregate interference from both on-board the aircraft as well as off-board, e.g. from a distribution of ground based emitters.

## **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 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. The first two are new in this assessment; the others have been updated from the previous report.

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 Intra-and Inter-system interference (i.e.; from GPS, Galileo, and SBAS satellite signals) to L1 C/A code 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.

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 substantially updated and a new saturating pulse RFI effect derivation is added. Appendix E (receiver RFI performance emulation and simulation) legacy material has been retained and substantial new material added on GNSS intra- and inter-system RFI, aggregate cockpit case-radiated and PED RFI. Appendix F (standard received signal and interference environment) shows the RTCA/DO-229D MOPS Appendix C content marked with proposed changes. Appendix G (Installed Aircraft GNSS Antenna Performance Model) has been updated with new 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 was combined with previous L1 report Appendix J noise equivalency factor material. Legacy material has been retained in Appendix I (Line-of-Sight Propagation from Multiple RFI Sources) and substantial new material on aggregate terrestrial RFI modeling has been added. New 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 L1 report for historical reference purposes. Legacy material from the previous L1 report Appendix L has been deleted as no longer needed. New Appendix L is reserved. Appendix (M 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 aggregate RFI effect model for a distribution of terrestrial RFI sources out to the aircraft antenna radio horizon. That model was used to estimate a mean source RFI emission power 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 consumer and commercial devices are only now available for purchase. At this time, UWB wireless hubs and enabled laptop computers are the only devices available. It is still too early to determine whether the rules will protect GPS from interference from a practical standpoint. The ITU-R has abolished Task Group 1/8 since it completed its work and generated Reports and Recommendations (ITU-R SM.1757). Despite this, Question Q.227/1 is still open and further studies may be conducted.

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. New 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 source 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 intra- and inter-system RFI effects have been investigated in detail for this report. The effects explicitly addressed are a larger GPS satellite constellation with new signals along with new SBAS and new RNSS systems from other countries such as QZSS and Galileo. These effects can be effectively mitigated by appropriate satellite signal design.

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 1559-1605 MHz for broadband emissions.

Fixed Service operations that exist in many foreign countries in the 1559-1610 MHz band are being phased out in order to protect GNSS operations in their countries.

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. Methods for rapidly locating and identifying individual sources of RFI at levels sufficient to

interfere with GNSS services are needed. The FAA is currently implementing an aggressive GPS RFI monitoring system at airports. It is developing direction-finding techniques, which range from fixed sites to transportable devices, airborne capabilities, and handheld devices.

### **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.

LAAS and WAAS MOPS-compliant receivers must satisfy certain performance parameter requirements (e.g., pseudorange error, WAAS 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 the 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 still explicitly included in Category I 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**

Three scenarios from the original RTCA/DO-235 report were reviewed and updated. 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 (dependant on aircraft receiver equipage). The minimum separation distance for Category I Precision Approach remains the same value but has two new associated

probability values (dependant on autopilot use). Two new scenarios were developed for the L1 assessment update: Category II/III Precision Approach, and Surface Movement. The scenario parameters for separation distance, associated probability, and antenna gain toward the RFI source are summarized below (Table 1). These parameters for the propagation path were used in the subsequent link analyses for significant RFI sources.

**Aeronautical RFI Encounter Scenario Parameters**

<b>Scenario</b>	<b>Obstacle Separation Dist. (feet)</b>	<b>Ant. Height (feet)</b>	<b>Probability of smaller distance</b>	<b>Rcv Ant. Gain (RFI)</b>	<b>Comments</b>
Enroute/ Terminal Area	500 (min)	18000 / 1756	N/A	Use Cat I Model	Operation in some regions results in 1000' min. separation
Non-Precision	100	various	$5.2 \times 10^{-3}$ (-208) $1.6 \times 10^{-3}$ (-229D)	Use Cat I Model	RTCA/DO-229 receiver has lower NSE than -208
Category I	96.7	175	$< 1 \times 10^{-6}$ auto $2.8 \times 10^{-4}$ manual	Cat. I Model	
Category II/III	70	85.1	$1 \times 10^{-7}$	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-235A are retained unchanged in this new assessment report. No material was submitted to update them.

### **GPS-Aided Enhanced-911 Cellular Telephone Position Reporting**

E911 deployment will likely rely 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<sup>2</sup> broadband and -157.7 dBW/m<sup>2</sup> narrowband) are still proposed as single-entry values in coordination. The recently authorized 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 additional potential 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 10 sources equals 15% of the system thermal noise. More effort is needed to verify that estimate and improve RTCA/DO-160 test limits and procedures.

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. An on-board aggregate PED RFI density estimate is made that equals the MOPS enroute RFI test condition. 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 than 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 LAAS 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 (3<sup>rd</sup> harmonic) and the Channel 66 sound carrier (2<sup>nd</sup> harmonic) which fall within 0.33 MHz and 0.08 MHz, respectively, of GPS L1. Field measurements of harmonic levels have shown, however, that TV harmonic suppression is actually more than 40 dB greater than the minimum 60 dBc requirement. Analog TV RFI to GNSS is therefore not a problem. Digital TV RFI to GNSS (newly assessed in this report) is also shown not to be significant due to engineering, regulatory, and frequency management factors.

### **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 new 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 a 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-235A report and updated for FCC regulatory actions. 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 Intra-and Inter-System Interference**

A detailed methodology for analyzing GNSS intra-system and inter-system interference is developed in this report. The “critical satellite” concept is used to determine the maximum aggregate received effective interference power spectral density that can be received from the GPS satellites in view in those critical situations. The analysis has shown that the most significant source of self-interference to C/A code is the 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. However, for this assessment that effect is modeled by a constant (average) spectral separation coefficient 1.8 dB larger than the “long code” value. Cumulative probability distribution functions are derived for the for GPS intra-system interference PSD at various operationally significant locations. The GPS values at 0.999 upper bound probability are combined with SBAS and other inter-system components present at each location to form the aggregate GNSS interference PSD. These values are used in the RFI link analyses summarized in 15.3.5.

### **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) and signal tracking (GPS and WAAS). The main analysis objectives were to assess the RFI compatibility of GNSS L1 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. This composite is proposed to be the replacement for the recently introduced “GNSS self-noise” test condition in the L1 receiver MOPS. As a result, the present RTCA/DO-229D MOPS values for SBAS signal tracking / reacquisition and for GPS acquisition should be increased 0.2 dB and 0.7 dB, respectively, while the GPS signal tracking/reacquisition value should remain unchanged. The estimated aggregate cockpit equipment case-radiated RFI component, determined from sample radiated emissions test results, should be verified by additional measurement and analysis. RTCA/DO-160E Section 21 radiated emission limits (Category M and H) should be reduced in the GNSS L1 band and the related test procedure revised to help assure proper compatibility for GNSS installations.

### **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-229D 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.

Aircraft altitude-dependent aggregate off-board non-aeronautical RFI was estimated by two methods: “continuum area” emitter and “randomized discrete” emitter. Terrestrial RFI sources for both methods were assumed to be distributed uniformly on a flat plane to the radio horizon for the particular antenna height in the scenario. With equivalent assumptions for the source emission level, these methods gave nearly identical estimates

for the mean received RFI. The “randomized discrete” emitter method yielded additional information on the received RFI standard deviation and the shape of the probability curve. Computations at several aircraft altitudes showed only a slow RFI decrease with increasing altitude. One result was that at 18000 feet the aggregate terrestrial RFI level was about the same as the on-board PED aggregate.

### **RFI Link Analyses Results Summary**

The LAAS Category I precision approach link analysis results show that at limiting-case signal and RFI conditions, the “minimum performance model” receiver tracking threshold performance is maintained (0dB link margin). The non-aeronautical RFI in the link is the RTCA/DO-229D MOPS precision approach “external” RFI test condition value. From this test condition, two main terrestrial RFI source constraints are derived: a minimum 64 m slant range to a nearby MSS MET and an average distributed RFI source emission PSFD (-121.31 dBW/MHz/m<sup>2</sup>). These are essentially RFI compatibility constraints that preserve a 6 dB aeronautical safety margin for the MOPS test condition. Although the single MSS MET source effect can be readily characterized, the aggregate RFI from a distribution of terrestrial sources is considerably more difficult to determine. Since this report represents the initial attempt to characterize the aggregate terrestrial RFI effect for GNSS receivers, the methods need further review and possibly refinement and their underlying assumptions need verification and validation.

The other Category I precision approach link analyses show acceptable positive link margins in the presence of limiting-case RFI and minimum satellite signals. Based on an extension of the 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 45° from nadir (-13 dBi vs. -10 dBi for Cat. I installations).

Link analyses for the other four 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. Although the links show positive margins with the higher terrestrial aggregate RFI, the applicable MOPS RFI test conditions (-143.5 dBW/MHz, NPA; -146.5 dBW/MHz, enroute and terminal area) do not adequately reflect the non aeronautical RFI and still preserve a 6 dB safety margin. The non-aeronautical (external) RFI composite values that should be used as 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 2500 feet AGL
- Signal tracking / reacquisition (enroute-only GNSS equipment) - increased 3 dB to -143.5 dBW/MHz and apply to all operations above 2500 feet AGL
- Acquisition (all GNSS equipment) – remain at -146.5 dBW/MHz).

### **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 – the practical methods have already been employed. Promising developments in navigation system susceptibility reduction that are closer to actual deployment are the use of tightly coupled inertial measurement units, and the use of a second frequency (GPS L5).

## **Recommendations**

The following recommendations from the previous assessment, RTCA/DO-235A, are still applicable. Assignees are shown in parentheses

1. MSS MET manufacturers should be required to demonstrate continued compliance to the emission limits by i) short-term testing of high risk elements that affect the terminal output power, and ii) analysis that estimates the mean time between failures (MTBF) of these high risk elements. (FCC, NTIA, FAA)
2. Current unwanted emission limit regulations should be reviewed for equipment that could potentially cause harmful interference to GNSS receivers. The long-term goal would be to tighten those limits in order to reduce the noise floor and allow more efficient use of that spectrum. (FCC, NTIA, FAA)

Recommendations from the current assessment are listed below.

3. RTCA/DO-160 radiated emission limit and measurement procedure issues raised by RTCA SC-159 with RTCA SC-135 have resulted in partial changes in the RTCA/DO-160F final draft. Further work is needed in the near term by the RTCA SC-135 community in coordination with RTCA SC-159 to address more completely the standards to limit on-board installed equipment case-radiated RFI emission limits in the frequency band used by GNSS. (RTCA SC-135, RTCA SC-159)
4. Aircraft certification criteria for GPS “disruption” should be reviewed with consideration of the stringent WAAS MOPS regulatory requirements for satisfactory operation in the presence of RFI and the fact that there is no requirement (except for specific MOPS citation) for on-board equipment to meet the RTCA/DO-160 limits. (FAA)
5. Although considerable portable electronic device RFI emission test data have been gathered and made available, more detailed emission measurements need to be made to better model the emission characteristics (noise-like, discrete, other type) and radiation patterns for use in future GNSS L1 and L5 susceptibility analyses. (FAA, NASA, NTIA, FCC)
6. GNSS receiver MOPS RFI test conditions for “GNSS noise” have been reassessed to account for operationally significant GPS constellation situations with up to 30 satellites. These test conditions should be broadened to also include a component for other aeronautical continuous RFI. As such the new RFI test conditions for SBAS tracking / reacquisition and for GPS acquisition should be changed to  $-172.8$  and  $-172.2$  dBm/Hz, respectively. Due to offsetting corrections, the GPS signal tracking / reacquisition should remain at  $-171.9$  dBm/Hz. (RTCA SC-159)
7. To better account for the aggregate effects of terrestrial RFI sources distributed to the radio horizon and of on-board PEDs placed throughout the passenger cabin, the application of GNSS receiver MOPS “external RFI” test conditions should be revised. The “precision approach / Satcom-equipped” value ( $-110.5$  dBm/MHz) should now apply to all GNSS receivers that need to operate at or below 2500 feet

AGL. GNSS receivers that only operate above 2500 feet AGL should now be tested at -113.5 dBm/MHz (formerly the “NPA” value). The acquisition test limit should remain unchanged at -116 dBm/MHz. (RTCA SC-159 (MOPS as required), FAA (TSO’s as required))

8. An extensive investigation should be undertaken to verify and refine the aggregate terrestrial received RFI predictions of this report at the various locations and heights above ground for the GNSS L1 band. The investigation should include both field tests and detailed modeling to refine such assumptions as the present  $r^{-2}$  propagation assumption. The GNSS L5 band should also be included if possible. (FAA, NASA, NTIA)
9. Since GPS re-radiator RFI acts potentially like strong multipath, fixed re-radiators should not be authorized at locations near airport runway approaches, especially the DH or MAP waypoints. (NTIA, FAA)
10. If GPS is to become a critical element in aeronautical navigation and surveillance, improved capability is needed to promptly detect and characterize interference from external sources, localize those sources, and neutralize them. Necessary aspects are improvements to the reporting process, an effective method of assessing interference mechanisms, a capability to trace the interference to its source, and the legal framework to negate it at the source. Although many elements of this required capability are in place or in development, they must be combined into an effective overall interference-elimination process. (FAA)
11. Since interference to GPS impacts many areas besides aviation, this process necessarily involves government organizations involved in those areas as well. The systems operated by the various agencies for the detection and characterization of interference to GPS should be integrated and coordinated, and agencies should work cooperatively to minimize the time it takes to trace interference in the GPS bands to its source. Legal aspects should be strengthened to allow rapid negation of the interference once it has been identified and localized. (FAA, NTIA, FCC, DOT, DHS)
12. Develop more comprehensive modeling of inter- and intra-system L1 GNSS interference that includes (1) simulation of larger GPS constellations with elevation angle statistics; (2) application of the inter-satellite differential Doppler at each time step and the effect on the spectral separation coefficient (SSC); (3) interference from other RNSS systems as their plans evolve; (4) analysis of a WAAS Demod link at a location with a 5-degree elevation angle to the WAAS GEO. (RTCA SC-159)

## 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 early system configuration should be expanded to accommodate the Russian Federation GLONASS and other satellites and augmentations as they become available.” 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 general 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 navigation signals considered were the GPS and GLONASS Standard Positioning Service (SPS) signals on their respective L1 carriers, and the L1 signals transmitted by the FAA Wide Area Augmentation System (WAAS).<sup>1</sup> 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/WAAS 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 ( $1176.45 \pm 12$  MHz) and determine appropriate receiver susceptibility criteria and related RFI unwanted emission

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<sup>1</sup> Future planned civil enhancements/augmentations to the GNSS will include signals on other carriers (e.g., GPS, L5 and the European Galileo). As with the previous report, this update will not specifically address RFI issues associated with performance of these future signals. An initial GNSS L5/E5A assessment report has been completed and published in 2004 as RTCA/DO-292.