Methodology for Determining Compatibility of GPS L5 with Existing Systems and Preliminary Results*

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BIOGRAPHIES

Dr. Christopher Hegarty is a Project Team Manager at The MITRE Corporation. He received his B.S. and M.S. from Worcester Polytechnic Institute, and his D. Sc. from The George Washington University. He was a recipient of the 1998 ION Early Achievement Award, and currently serves as Editor of *Navigation*: *Journal of the Institute of Navigation* and as co-chair of RTCA SC159 Working Group 1 (2nd Civil GPS Frequency).

Taehwan Kim is a Lead Engineer at The MITRE Corporation. He received his B.S. in mathematics from the Seoul National University, M.S. in computer science from the University of South Carolina, Columbia, and is currently working toward his Ph.D. EE at The University of Maryland, Baltimore County. Since 1987, he has held several industry positions in the areas of radar and satellite communication engineering.

Swen Ericson is a System Development Engineer at The MITRE Corporation. He received his B.S. degree in Civil Engineering from The University of Miami, FL in 1992, and M.S. in Surveying Engineering from Purdue University in 1994. He has recently been involved with GPS modernization studies at MITRE/CAASD.

Patrick Reddan received his B.E.E.E. from Manhattan College and the Degree of Engineer (EE) as well as Master in Engineering Administration from George Washington University. He joined Zeta Associates in 1986 and is currently providing support to the FAA WAAS program development. Particular areas of interest include system architecturing as well as signal processing and interference mitigation techniques.

Dr. Thomas Morrissey received his BSEE from the University of Notre Dame, his SMEE from the Massachusetts Institute of Technology, and his Ph.D. in EE from the University of Notre Dame. He served in the US Army from 1968-1970, worked in private industry from 1971-1975, and held research and analytical positions with the Central Intelligence Agency from 1975-1998. He joined Zeta Associates in November 1998 and is currently providing support to FAA programs.

Dr. A.J. Van Dierendonck received a BSEE from South Dakota State University and MSEE and Ph.D. from Iowa State University. Currently, he is self-employed under the name of AJ Systems and is a general partner of GPS Silicon Valley. In 1993, Dr. Van Dierendonck was awarded the Johannes Kepler Award by the Institute of Navigation Satellite Navigation Division for outstanding contributions to satellite navigation. For 1997, he was awarded the ION Thurlow award for outstanding contributions to the science of navigation. A.J. has 25 years of GPS experience and is a Fellow Member of the IEEE. He currently serves as working group co-chairman of the RTCA SC159 Working Group (WG1) for the 2nd Civil GPS Frequency.

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ABSTRACT

This paper describes the methodology being used by an ad hoc working group of the Interagency GPS Executive Board (IGEB) Third Civil Signal Implementation Steering Group to address the feasibility of coexistence between the third civil GPS signal and existing systems at or near 1176.45 MHz. The paper also describes preliminary results of applying this methodology to known emitters in the U.S. and other regions of the world.

INTRODUCTION

On January 25, 1999, U.S. Vice President Al Gore announced that two new civil GPS signals will be added to future GPS satellites [1]. The second civil signal will use the C/A codes currently used at GPS L1 (1575.42 MHz) and will be located at GPS L2 (1227.6 MHz). The third civil signal, which is intended to meet the needs of critical safety-of-life applications, will be located at 1176.45 MHz (L5). The second and third civil signals are anticipated to be included on GPS satellites that will be launched beginning in 2003 and 2005, respectively.

To address issues related to the implementation of the third civil signal, the Interagency GPS Executive Board (IGEB) has established a steering group and four ad hoc working groups (see Figure 1). This paper describes the initial findings of ad hoc Working Group 1 (WG1) that was chartered to "…address the feasibility of providing a protected safety-of-life GPS signal suitable for civil aviation use while allowing existing, authorized systems to coexist…" [2]. More specifically, this paper:

1. Describes existing systems operating at or near 1176.45 MHz.
2. Introduces the methodology being used by ad hoc WG1 to determine compatibility.
3. Presents preliminary results using this methodology.

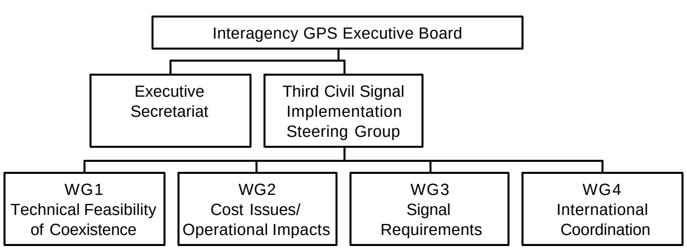

Figure 1. IGEB Third Civil Signal Implementation Steering Group Organization

EXISTING SYSTEMS OPERATING AT OR NEAR 1176.45 MHz

Major existing systems operating at or near 1176.45 MHz include:

1. Aeronautical systems operating between 960 and 1215 MHz – including Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN) systems, that operate throughout the band, and the systems that operate at 1030 and 1090 MHz, including Secondary Surveillance Radars (SSR), Traffic Collision and Avoidance System (TCAS), Identify Friend or Foe (IFF) and planned Automatic Dependent Surveillance – Broadcast (ADS-B). The Federal Aviation Administration (FAA) operates approximately 1000 DME and TACAN beacons. The U.S. Department of Defense (DoD) operates an additional 173 TACAN beacons [3].
2. Joint Tactical Information Distribution System/Multi-functional Information Distribution System (JTIDS/MIDS) operating between 969 and 1206 MHz – a spread-spectrum digital communications system used by the DoD and other nations to exchange data among military platforms. JTIDS is currently deployed on about 600 platforms in its Class 2 form. They are installed on F-14 fighters, a squadron of F-15 fighters, Navy E-2Cs, ships, E-3 airborne early warning platforms, Modular Control Equipment, ABCCC, Rivet Joint, and Joint STARS platforms. MIDS is under development as the next-generation version of JTIDS and will eventually be deployed on about 2400 U.S. platforms by the year 2005.
3. Military and civil radars operating between 1215 and 1385 MHz – including about 250 systems in the U.S. used for long-range primary air traffic control (ATC), the North Warning System (NWS), drug interdiction, and other applications.

One common characteristic of all of these systems is that they are pulsed. This commonality facilitates the coexistence of these systems with L5, since GPS receivers can be made very robust against pulsed interference. Details on these systems are provided in the following subsections.

DME/TACAN

DME and TACAN are navigation systems that provide airborne interrogators with distance measurements from ground transponders via pulse ranging (TACAN provides azimuth information as well). DME and TACAN operate over much of the 960 – 1215 MHz band with a channel spacing of 1 MHz. Of the four modes (X, Y, W, and Z) used by DME/TACAN, only the X-mode replies that span 1151 – 1213 MHz fall in-band with respect to the L5 signal. The X-mode ground transponders (beacons) transmit pulses in pairs with a pulse separation of 12 μs and a repetition rate of around 2700 pulse pairs per second (ppps) for DME, and 3600 ppps for TACAN. These repetition rates are maintained even when aircraft interrogations are not being received. The pulse shape is nominally gaussian (see Figure 2). The one-half voltage pulse width is 3.5 μs.

The ground beacons transmit with a peak Effective Isotropic Radiated Power (EIRP) ranging from 100 to 10000 W. Typical antenna gain patterns are shown in Figure 3. Most (around 87.5 percent) of the radiated power is contained within a 0.5 MHz bandwidth centered on the 1 MHz channels.

DME and TACAN beacons are situated throughout the U.S. to provide aircraft navigation for en route through non precision approach phases of flight. In certain regions, many DME/TACANs are visible at high altitudes, notably the East Coast, and airspace surrounding Chicago and Los Angeles. For example, Figure 4 shows the DMEs and TACANs with frequency allocations from 1157 – 1209 MHz surrounding Harrisburg, Pennsylvania. A simulated sample of the signal that would be received by an airborne GPS/WAAS receiver with a 20 MHz passband at 40,000 ft above Harrisburg is shown in Figure 5. For reference, the assumed noise floor in the passband is at –97 dBm. As will be shown, this level of interference is not acceptable. As a solution to this problem, WG1 has considered reassigning the frequencies of some or all of the DME/TACANs that currently fall within 10 MHz of L5.

Other Aeronautical Systems

WG1 has found other aeronautical systems (e.g., DME/TACAN interrogators, SSR, IFF, TCAS) operating in the 960 – 1215 MHz band to be very minor contributors to the electromagnetic environment around 1176.45 MHz. These systems do not operate inband to L5 and are pulsed with low duty cycles.

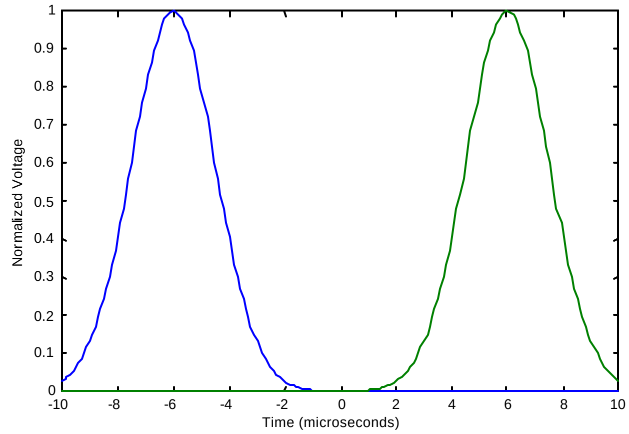

Figure 2. DME/TACAN X-Mode Pulse Pair

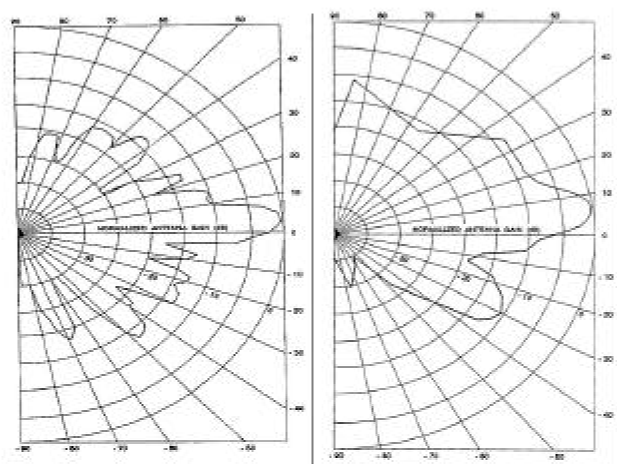

Figure 3. Typical DME (Left) and TACAN (Right) Antenna Gains vs. Elevation Angle (Peak Gain Minus Cable Losses is 6-9 dBi)

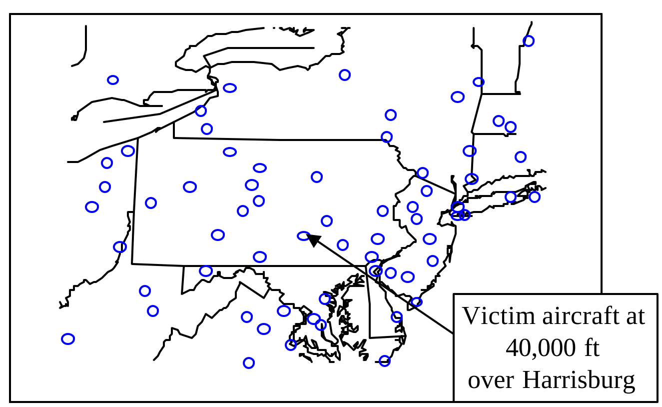

Figure 4. DME/TACANs Surrounding Harrisburg, Pennsylvania

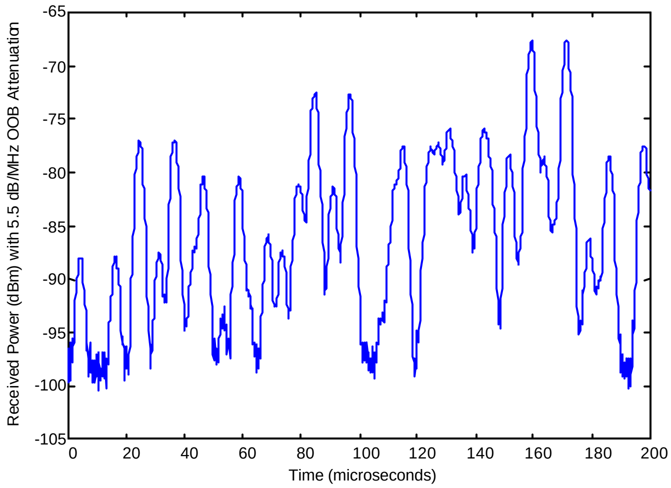

Figure 5. Signal Received by an L5 GPS/WAAS Receiver 40,000 ft Above Harrisburg

JTIDS/MIDS

JTIDS and MIDS operate over 51 frequencies between 969 and 1206 MHz (see Figure 6). Airborne platforms equipped with JTIDS/MIDS may have top and bottom mounted antennas (see Figure 7 for a typical bottom-mounted gain pattern).

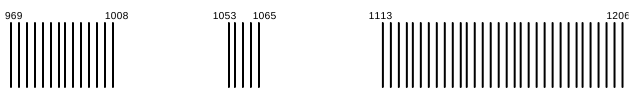

Figure 6. JTIDS/MIDS Carrier Frequencies

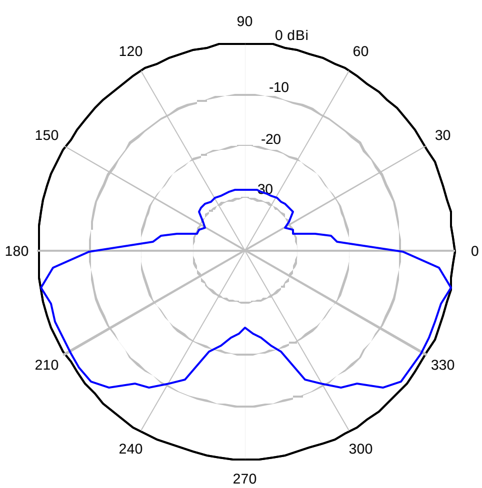

Figure 7. F-15 JTIDS Bottom Mounted Antenna Gain vs. Elevation Angle

To ensure compatibility between JTIDS and other systems (e.g., DME, TACAN, secondary radars) in the 960 – 1215 MHz Aeronautical Radionavigation Service (ARNS) band, the National Telecommunications and Information Administration (NTIA) has levied a set of electromagnetic compatibility (EMC) requirements upon JTIDS transmissions [4], including the pulse spectrum rolloff specification shown in Figure 8. Importantly, although the rolloff specification only calls for the noise floor to be 60 dB down from the carrier beyond 15 MHz from the carrier frequency, in order to meet EMC monitoring requirements to protect systems operating at 1030/1090 MHz, JTIDS equipment as currently implemented must maintain a noise floor at least 67.4 dB lower than the carrier [5].

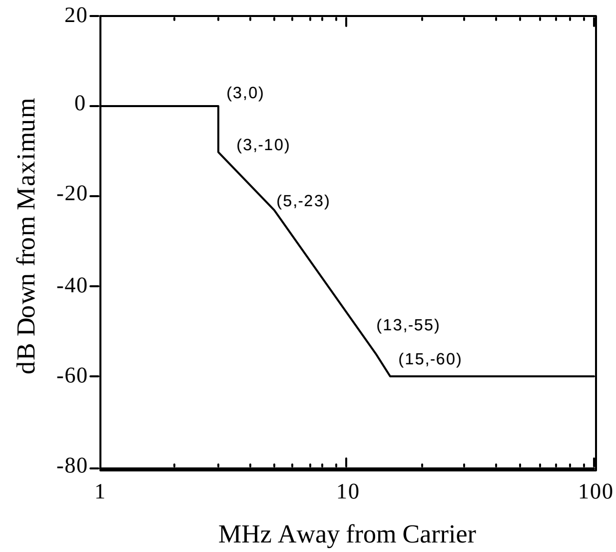

Figure 8. JTIDS Pulse Power Rolloff Specification [4]

NTIA EMC requirements call for JTIDS and MIDS terminals to monitor their emissions. Each terminal is required to inhibit transmissions when emissions exceed specified limits. JTIDS and MIDS terminals monitor emissions in accordance with one of four operator selected EMC protection modes. These modes are:

- 100/20 Full EMC Protection mode
- 100/50 Full EMC Protection mode
- Exercise protection mode
- Combat mode

In the two full EMC protection modes, 100/20 and 100/50 are percentages of 396,288 pulses allowable in a 12 second interval by all terminals and a single terminal operating in a geographic area, respectively. In the U.S., the geographic area (GA) is defined to be a circle with a 200 nmi radius. Many nations in Europe, including Belgium, Denmark, France, The Netherlands, Germany, Greece, Italy, Norway, and Turkey have smaller GAs of 100 nmi radii or less, while others (e.g., U.K.) have larger GAs.

There are several other emission characteristics that are monitored in the full EMC protection modes, including notably a 200 W transmit power limit, uniform frequency distribution across the 51 frequencies, and maximum emission power in bands surrounding the frequency pair 1030/1090 MHz.

For exercises in which the full EMC Protection modes are too restrictive, the DOD must coordinate with the FAA to use the Exercise protection mode. This mode is typically used for large scale training exercises, and during peacekeeping missions. The DOD would like to have the 200 nmi GA reduced in the U.S. to avoid the need for coordinating smaller exercises.

Finally, the combat mode is used in operations in which a transmission inhibit would deny warfighting forces needed threat information or jeopardize an engagement with hostile forces. This mode is used in situations where all the features and transmission power of the terminals are needed.

RADARS

Out-of-band (OOB) emissions from radars operating between 1215 – 1385 MHz in the U.S. was initially a significant concern for WG1. Although L5 is almost 40 MHz below 1215 MHz, the extremely high radiated power levels of many of these systems (tens of kilowatts to Megawatts) results in non-negligible OOB power levels at 1176.45 MHz, even through the antenna sidelobes. Furthermore, some of the radars have transmit modes that include very long (on the order of 1 ms) pulses that could be especially disruptive to GPS L5. OOB spectrum measurements obtained for several of the radars indicated that peak OOB emissions are only 55 dB below inband power levels.

Closer scrutiny of the OOB emission characteristics of the radars revealed that OOB emission are characterized by short (less than a few hundred nanoseconds) spikes of power, corresponding to the rise and fall times of the radars' inband pulses. These spikes dominate the spectrum measurements. In between these spikes, the OOB emissions are much lower.

With proper accounting for the time characteristics of radar OOB emissions, radars were not found by WG1 to be significant contributors to the electromagnetic environment around 1176.45 MHz.

SIGNAL-IN-SPACE ASSUMPTIONS

As shown in Figure 1, IGEB Third Civil Signal Implementation Steering Group ad hoc Working Group 3 (WG3) has been chartered to define the requirements for the new signal. WG3 has, in turn, been relying on RTCA Special Committee 159 Working Group 1 (SC159 WG1) to achieve consensus on the signal design. This section summarizes the most recent signal design [6] that has been recommended by SC159 WG1 and endorsed by WG3. Further background on the development of the signal design may be found in [7].

The proposed GPS L5 signal is comprised of a pair of carriers (inphase and quadrature) at 1176.45 MHz that are Binary Phase Shift Keying (BPSK) modulated by:

- 10.23 Mchip/s spreading sequences – The inphase and quadrature carrier channels are BPSK modulated by different sequences (see [6] for details of the spreading sequences). Length 10230 sequences will be employed, resulting in a 1 ms repetition period.
- The inphase signal is BPSK modulated by data. The data rate is 50 bps. A rate ½ forward error correction (FEC) code is employed, yielding 100 symbols per second (sps).
- The inphase signal is BPSK modulated by a 1 kHz Neumann-Hoffmann sequence to improve symbol synchronization and cross-correlation properties.

The proposed WAAS L5 signal structure is similar, except that only a single carrier is used, and the data rate is 250 bps. A rate ½ FEC code is employed yielding 500 sps.

The GPS L5 minimum received signal power into a 0 dBic antenna at or near the surface of the earth will be –154 dBW. This level is 6 dB higher than the specified minimum power for the C/A code on L1 and facilitates coexistence with the emitters analyzed in this study. For GPS, one-half the power (-157 dBW) is provided to each carrier component (inphase and quadrature). For WAAS signals at L5, WG1 has been assuming the signal power will be at either –154 dBW or –151 dBW (since these satellites have not yet been designed, there is greater flexibility). All WAAS power is devoted to the inphase carrier.

RECEIVER ASSUMPTIONS

To facilitate coexistence, it is assumed that GPS/WAAS L5 receivers will employ some form of pulse detection and pulse blanking circuitry as well as better out-of-band filtering relative to current civil equipment operating at L1. The pulse detection circuitry detects when pulsed energy is being received above a certain threshold that is set relative to the nominal level of noise in a receiver's passband. When a pulse is detected, the input signal level is zeroed ("blanked"). Blanking is equivalent to excluding a portion of the received signal from the complex correlation sums generated by the receiver. Although the blanking threshold would be set adaptively relative to the nominal noise floor in a practical implementation, WG1 has conservatively assumed a fixed input level threshold of –86.5 dBm.

The assumed out-of-band filtering requirement is shown in Figure 9. A combination of radio frequency (RF) and Intermediate Frequency (IF) filters provides a total of 5.5 dB/MHz attenuation for interfering signals that fall beyond 10 MHz of L5. The maximum attenuation is 70 dB. Participants in RTCA SC159 WG1 have recommended use of a higher (5 dB) noise figure for L5 GPS/WAAS receivers than is specified in [8] for L1. This recommended increase is due to the anticipated greater filter insertion loss resulting from the more stringent filtering requirement. Combined with a 100 K sky noise, the 5 dB noise figure results in a receiver noise floor at –200 dBW/Hz.

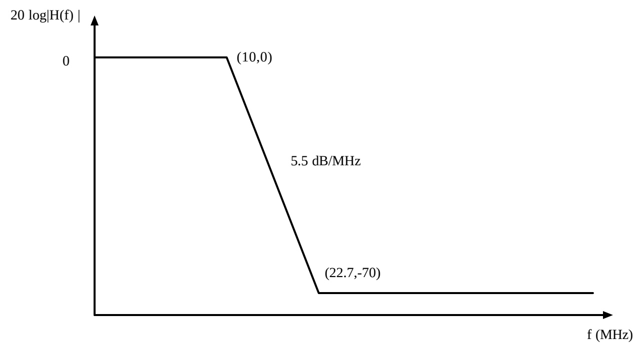

Figure 9. Assumed GPS/WAAS L5 Receiver RF/IF Filter Response

METHODOLOGY FOR DETERMINING COMPATIBILITY

The methodology for determining compatibility consists of determining the degradation to a GPS/WAAS L5 receiver's post-correlation signal-to-noise power density ratio (S/N_0) due to the presence of interfering signals. An acceptable level of degradation is defined to be one that yields 33.7 dB-Hz. This S/N_0 is attained at L1 for WAAS under the following conditions:

- Minimum received signal power of –161 dBW into a 0 dBic antenna
- –4.5 dBic antenna gain towards a desired low-elevation angle satellite
- 2 dB receiver implementation loss
- Maximum interference level of –122.5 dBm/MHz (-116.5 dBm/MHz to protect all receiver functions, including acquisition, from [8] adjusted by a 6 dB safety margin [9])

In the absence of interference, a minimum S/N_0 of 39.5 dB-Hz is expected (-154 dBW received power - 4.5 dBic antenna gain - 2 dB implementation loss - (-200) dBW/Hz noise floor = 39.5 dB-Hz). Compatibility is achieved at a geographic location, from a WG1 standpoint, if signals from existing systems do not result in more than a 5.8 dB degradation to the starting L5 S/N_0 (39.5 – 5.8 = 33.7).

An equation for computing the S/N_0 degradation to an L5 receiver is:

$$S/N_{0,\mathrm{eff}} = 39.5 + 20\log(1 - PDC_B)$$
$$-10\log\left(1 - PDC_B + \sum_{i=1}^{N} 10^{\left(\frac{R_i}{10}\right)}\right)$$

Where

$$(R_i)_{dB} = P_i + 97\ \mathrm{dBm} + 10\log dc_i\ ,$$

PDC_B (pulse duty cycle – blanker) is the total duty cycle of all pulses strong enough to activate the blanker, N in the total number of low-level undesired received signals (i.e., those not strong enough to trip the blanker), P_i is the peak received power of the i-th undesired signal, and dc_i is the duty cycle of the i-th low-level signal. The right-hand terms of the above equation are:

- 1st term – S/N_0 is the absence of interference
- 2nd term – Lost signal power due to the blanker
- 3rd term – Adjustment of the noise floor due to: (1) suppression of thermal noise by the blanker, and (2) noise floor contribution due to low-level pulses and continuous interference.

Use of the equation to predict an L5 receiver's performance in the presence of many undesired pulsed signals is only valid when the pulses are very short relative to the minimum predetection integration time used by the receiver (1 – 10 ms, depending on the mode of operation). This constraint is satisfied for DME/TACAN, JTIDS/MIDS, and most radar OOB emissions.

Note that the equation conservatively assumes that low-level pulses do not coincide with strong pulses that trip the blanker. Figure 10 plots the acceptable combinations of strong pulses and low-level interference (low-level pulses and continuous interference). Note that if there are no low-level pulses present, the blanker permits the receiver to operate in the presence of undesired signals with very high duty cycle (over 70 percent). Of course, any environment that includes high-level pulses in some regions, will also have larger regions with many low-level pulses. Thus, the likely operating point of the curve in Figure 10 is towards the right side – lots of low-level pulses and a low total duty cycle of high-level pulses.

It is very important to carefully define the meaning of "duty cycle" for both PDC_B and dc_i. Although the usual first step of defining duty cycle as the product of pulse width (PW) and pulse repetition frequency (PRF) is unambiguous, PW definitions vary greatly among systems. For instance, DME PWs are defined by half-voltage, whereas JTIDS pulses are defined by 90 percent power. The definitions that must be used to yield correct results using the above formula are:

$$dc_i = PW_i \times PRF_i$$

$$PW_i = \frac{1}{P_i}\int_{-\infty}^{\infty} p(t)dt$$

for low-level pulses where p(t) is the instantaneous received power of the pulse.

As an example, the instantaneous received power of a perfectly gaussian-shaped (not the case in reality, but a good first approximation) DME pulse can be written as:

$$p(t) = P_i e^{-\alpha t^2}$$

where $\alpha = 4.5 \times 10^{11}$ s^{-2}. The half-voltage pulse width is 3.5 μs, but PW_i as defined above is 2.6 μs.

For strong pulses, pulse widths should be defined by the time period that the instantaneous received power exceeds the blanker threshold.

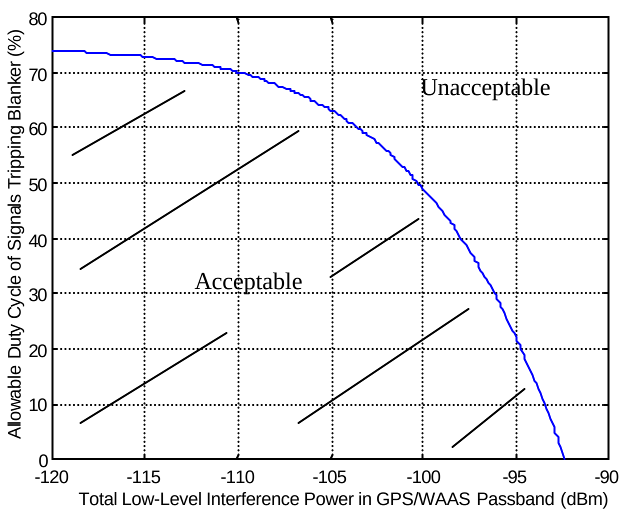

Figure 10. Acceptable Combination of High-Level Pulses and Low-level Interference

PRELIMINARY RESULTS

Using the assumptions and methodology described in the previous sections, interference analyses were performed using the GPS RFI Environment Evaluation Tool (GREET), a software tool developed by The MITRE Corporation's Center for Advanced Aviation System Development. Interference scenarios in both the conterminous U.S. (CONUS) and Europe were evaluated on a half-degree grid. Maps showing signal-to-noise ratio degradation at grid points of different flight altitudes were generated for different emitter configurations (see Figures 11-20).

Figures 11-13 show signal-to-noise degradations in the U.S. for various flight levels. Each of these plots includes effects from:

- DME/TACAN ground beacons
- JTIDS/MIDS – Calculations for each grid point reflect the effects of a 200 nmi JTIDS GA centered at that grid point assuming maximum allowable pulse density in the 100/50 Full EMC Protection mode.
- OOB emissions from radars
- Aeronautical emitters – A conservative allowance for emissions from DME/TACAN interrogators, SSR interrogators and transponders, TCAS, and ADS-B was included.

Note that signal-to-noise degradation is very dependent on altitude. At 40,000 ft above mean sea level (MSL), many ground-based emitters can be seen. Figure 11 indicates an unacceptable level of degradation at this altitude over large regions in CONUS. At 25,000 ft MSL (Figure 12), fewer emitters can be seen and the situation improves. At 5,000 ft above ground level (AGL) (Figure 13), the environment is very clean.

The high altitude electromagnetic environment surrounding 1176.45 MHz is dominated by DME/TACAN, as can be seen by comparing Figure 11 that includes all emitters with Figure 14 that only includes the effects of DME/TACAN. A very promising solution identified by WG1 is to reassign a subset of the inband DME/TACANs. Figure 15 plots signal-to-noise degradation due to all emitters with the inband DME/TACANs reassigned to other frequencies in the 960 – 1215 MHz band. The plot indicates that, with this DME/TACAN reassignment, an acceptable environment for L5 may be achieved throughout CONUS at this flight level.

Figures 16 – 20 show a similar sequence of plots for Europe. Figures 16-18 illustrate the effects of DME/TACAN, JTIDS/MIDS, and other aeronautical emitters on L5 at various altitudes over Europe. These figures should not be considered comprehensive as they do not include radars (authors did not have data available), and they assume a JTIDS/MIDS environment roughly consistent with a 100 nmi GA throughout Europe (not the case in reality, see earlier discussion on GAs). Similar to the results for the U.S., it appears that an unacceptable electromagnetic environment for L5 exists at high altitudes. DME/TACAN is the dominant contributor to this environment at high altitudes. As with the U.S., DME/TACAN frequency reassignments appear to be a promising solution for Europe.

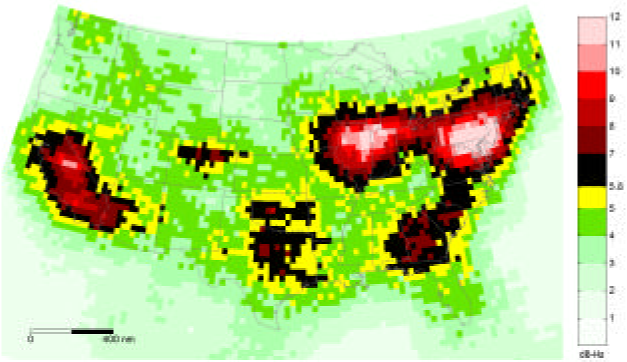

Figure 11. Total GPS Receiver Postcorrelation S/N_0 Degradation at 40,000 ft MSL over CONUS

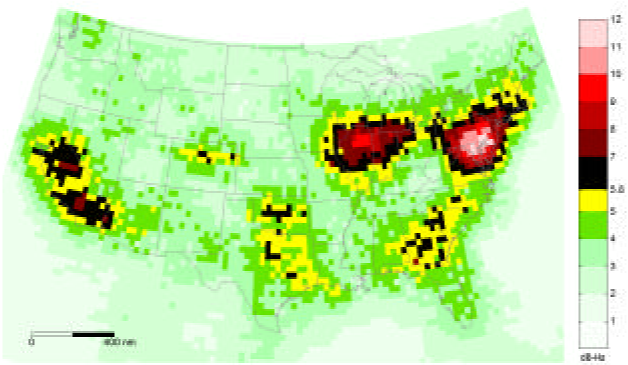

Figure 12. Total GPS Receiver Postcorrelation S/N_0 Degradation at 25,000 ft MSL over CONUS

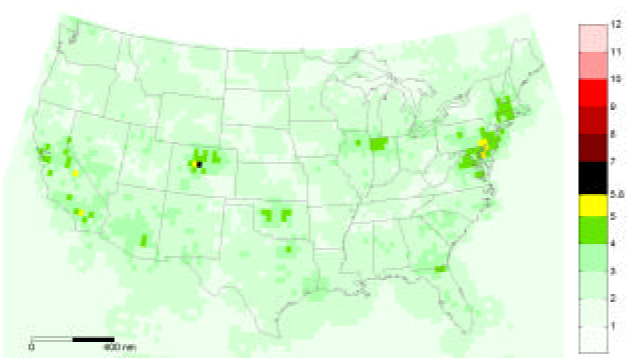

Figure 13. Total GPS Receiver Postcorrelation S/N_0 Degradation at 5,000 ft AGL over CONUS

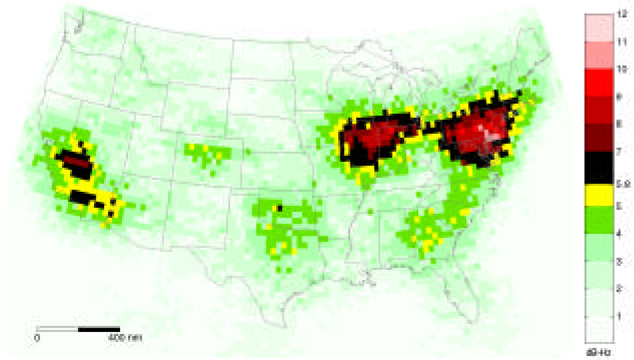

Figure 14. GPS Receiver Postcorrelation S/N_0 Degradation from DME/TACAN at 40,000 ft MSL over CONUS

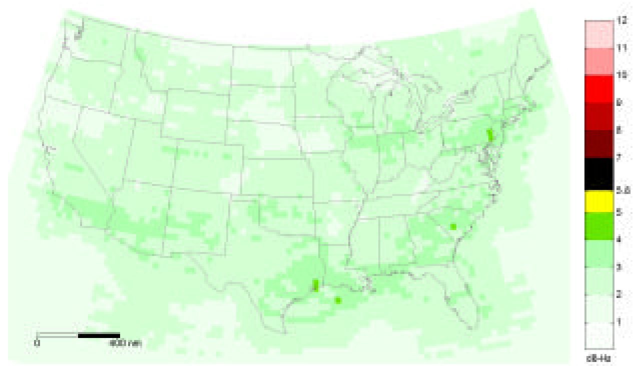

Figure 15. Total GPS Receiver Postcorrelation S/N_0 Degradation at 40,000 ft MSL over CONUS, DME/TACAN Emitters at 1176.45 ±10 MHz Reassigned

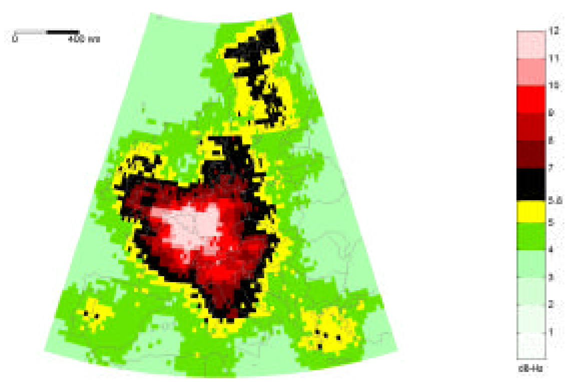

Figure 16. Total GPS Receiver Postcorrelation S/N_0 Degradation at 40,000 ft MSL over Europe

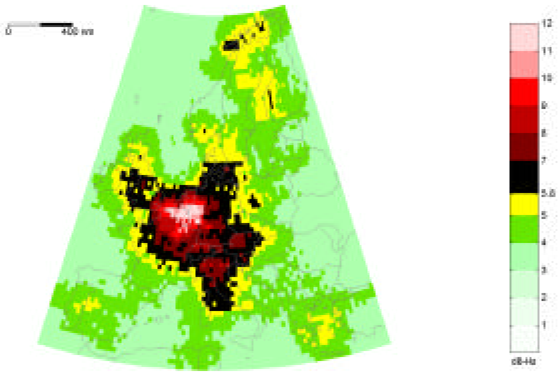

Figure 17. Total GPS Receiver Postcorrelation S/N_0 Degradation at 25,000 ft MSL over Europe

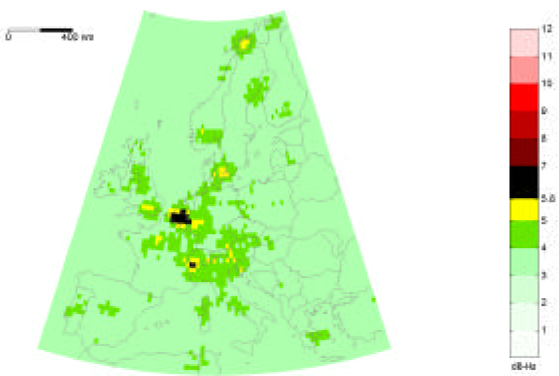

Figure 18. Total GPS Receiver Postcorrelation S/N_0 Degradation at 5,000 ft AGL over Europe

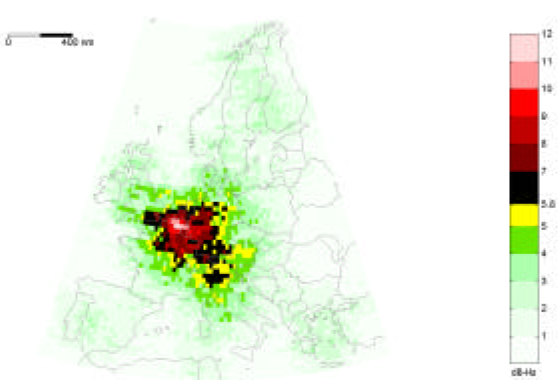

Figure 19. GPS Receiver Postcorrelation S/N_0 Degradation from DME/TACAN at 40,000 ft MSL over Europe

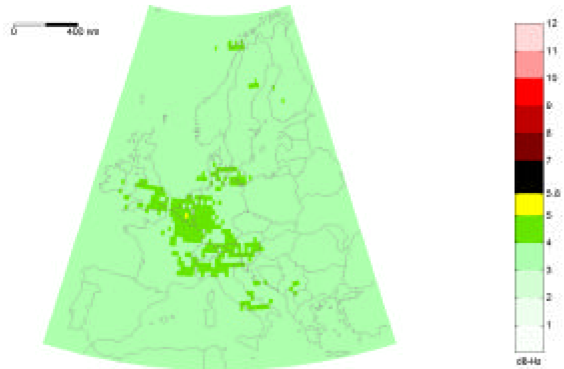

Figure 20. Total GPS Receiver Postcorrelation S/N_0 Degradation at 40,000 ft MSL over Europe, DME/TACAN Emitters at 1176.45 ±10 MHz Reassigned

CONCLUSIONS

This paper has described the methodology being used by an ad hoc IGEB working group to evaluate compatibility of the new civil GPS signal at 1176.45 MHz with existing systems operating at or near this frequency. Preliminary results indicate that on the surface of the earth and at low altitudes, no modifications to existing systems in the U.S. will be necessary to protect the GPS L5 service. At high altitudes, many more emitters are visible and present an unacceptable level of interference to the new signal. A promising solution to this problem is to reassign DME/TACAN frequencies that fall in-band to the new GPS signal.

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