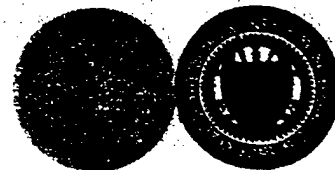


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Georgia Tech Project A-8348

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1.0 INTRODUCTION

1.1 Scope

This document is the final report of the Post Test Analysis (PoTA) phase of the Interceptibility Module of the Data Link Vulnerability Analysis Methodology (DVAL) as applied to the Global Positioning System (GPS) User Equipment (UE) developed by Rockwell/Collins. It continues and completes Georgia Tech's treatment of some issues first addressed under an earlier program, Contract N68787-86-3383, and described in a report entitled "DVAL Assessment of NAVSTAR GPS". That earlier report was the final report for the Pre-Test Analysis (PTA) phase of the Susceptibility and Interceptibility Modules of the DVAL Methodology.

It should be noted that the GPS UE, unlike many of the data communication systems that it is reasonable to evaluate with the DVAL methodology, does not intentionally transmit signals. Thus, the Interceptibility module does not play as big a role in the analysis of GPS jamming vulnerability as it would for other systems. Under this program the interceptibility module has not been emphasized to the same extent as the other three modules, which will be documented in forthcoming Georgia Tech reports.

As specified by the Joint Test Force that developed the DVAL Methodology, the Interceptibility Module is one component in a four-module assessment of the vulnerability of radio frequency data links in an electronic countermeasures environment. In the classical context, Interceptibility involves the determination of the probability that RF radiation from a communication system transmitter can be detected, that the source of that radiation can be identified and located, and that the characteristics of the radiated signal can be exploited to develop and mount a jamming attack against the link's receiver. This Interceptibility analysis deviates from this classical context in that

the specific device under consideration, the GPS UE, is a receiver-only system. Therefore, an analysis of "emissions" focuses primarily on unintentional emissions which may radiate from the GPS UE. The value of satellite uplink emissions, satellite downlink emissions, and UHF crosslink emissions is discussed; however, previous discussions have indicated that these emissions have little or no impact on the Interceptibility of the GPS UE. This Interceptibility evaluation relies primarily on analysis, discussions with appropriate military testing agencies, and discussions with Rockwell/Collins testing entities in an effort to assess Interceptibility. It also provides recommendations relative to further testing.

1.2 Report Organization

Section 2.0 briefly summarizes the findings of this report and associated recommendations. Section 3.0 summarizes the potential GPS UE emission sources, and provides a brief summary of findings from the previous report. In addition, this section focuses on potential GPS UE emissions that could hypothetically provide for Interceptibility concern. Section 4.0 addresses the feasibility of Interceptibility given the specified potential emission sources. Section 5.0 provides conclusions and discusses recommended testing and associated testing methodology. Potential Interceptibility testing that may be incorporated into the GPS UE OPEVAL is also addressed.

2.0 SUMMARY and RECOMMENDATIONS

From the investigation documented in this report, it has been assessed that the probability of Intercept of the GPS UE based on intentional system and unintentional UE emissions is very low. This report has generated potential worst case Intercept Receiver detection ranges based on the MIL-STD-461 CE06 and RE02 specified allowable upper levels. Near-Field determined RE02 limits for GPS UE unintentional emissions have been extrapolated to the Far-Field in an effort to get an estimate of the potential Interceptability of the GPS UE.

Under the following conditions, it is recommended that Far-Field radiated power measurements not be performed to assess Interceptability:

- . If, during the EMI/EMC MIL-STD-461 specification verification process, near-field measurements fall below the specified MIL-STD-461 levels.
- . If these measurements give good indication that far-field radiated levels are not excessive.

If these conditions are not met, and if the GPS UE is accepted with emissions above the specification level, this situation relative to Interceptability would require a reassessment.

3.0 DISCUSSION OF POTENTIAL EMISSION SOURCES

3.1 Intentional Emitters

This section briefly discusses the Interceptability issues pertaining to the Global Positioning System as a whole. Intentional emissions include the following:

- . Telemetry, Tracking, and Control (TT&C) Link
- . UHF Crosslink
- . L1 Downlink
- . L2 Downlink
- . L3 Downlink

Previous work (Section 8.0, "DVAL Assessment of NAVSTAR GPS") has evaluated these intentional emissions with regard to Interceptability of the GPS as a whole. Note that these previous findings indicated that the Interceptability of these intentional emissions had little or no effect on the Interceptability of the individual GPS UEs. These findings shall now be briefly summarized.

3.1.1 Telemetry, Tracking and Control (TT&C) Link

The value of intercepting the TT&C link appears limited. Jamming the uplink appears to be of little value because the system has such inherent stability that it can function for many days without updating orbital position data, with only a slow decay of GPS UE measured position accuracy. Jamming the downlink also appears of little value because alternative downlink/crosslink paths can provide required data to the Network Control Center (NCC).

Great obstacles exist even for highly coordinated jamming, interception, and spoofing. First, the data is heavily encrypted providing stringent controller/SV ID validation to prevent

spoofing. Second, TT&C data transactions take place primarily over United States airspace, limiting access to potential interceptors/jammers.

In addition, knowledge of TT&C communications activities does nothing to increase or affect the Interceptibility of individual GPS UEs; it is the interceptibility of the UEs that is emphasized by the DVAL methodology.

3.1.2 UHF Crosslink

Utilizing a priori knowledge of exact satellite positions would prove more beneficial than attempting to determine satellite positions via Integrated Transfer System UHF crosslink interception.

Highly coordinated ground-based jamming could hypothetically disrupt UHF crosslink information transfer. (No details have been obtained regarding GPS specific information transferred on the UHF crosslinks, making detailed analysis impossible.) If UHF crosslinks provide a relay network for almanac data transfer between GPS satellites, and the correct reception of this data is denied owing to highly coordinated jamming, then jammed satellites can simply rely on internally predicted almanac data updating with little or no overall GPS system performance degradation. In addition, individual satellite almanac data updating can be provided by the TT&C link once every 24 hour period. Under these assumptions, UHF crosslink interception/jamming would prove of little value. Note also that interception of UHF crosslinks would provide no information about the location of individual GPS UEs.

3.1.3 L1, L2 and L3 Downlinks

From a GPS UE intercept point of view, detailed knowledge of the L1/L2/L3 signals on the downlink would not provide the jammer

with any useful information pertaining to the location of individual GPS UEs.

Although knowledge of the downlink signals does not directly assist interceptability of GPS UEs, this information could be used by sophisticated deception or so called "pseudolite" jammers. This topic is addressed further in the "Susceptibility Module Post-Test Analysis Report" provided under this program.

3.2 Unintentional Emissions

Although the GPS UE functions solely as a receiver (and for that reason contains no deliberate transmissions that need to be assessed relative to interceptability) there are unintentional low level emissions which emanate from internal leakage sources. In the absence of deliberate emissions, these are the emission sources that are the closest to falling within the interceptability analysis concept.

Unintentional emissions from the GPS UE receivers consist primarily of radiated emissions from UE internal receiver local oscillators. Figure 3.1 illustrates a simplified block diagram of the RF portion of the Rockwell/Collins GPS UE.

A review of this figure indicates that potential GPS UE local oscillator emission sources consist of the following:

- . 1401.52 MHz LO
- . 350.38 MHz LO Reference
- . 10.23 MHz LO Reference and Harmonics

Interceptability based on the analysis of emission of the above mentioned potential sources focuses on radiation from the receive antenna, radiation from RF and IF cables and connectors, and radiation from the GPS UE case and components.

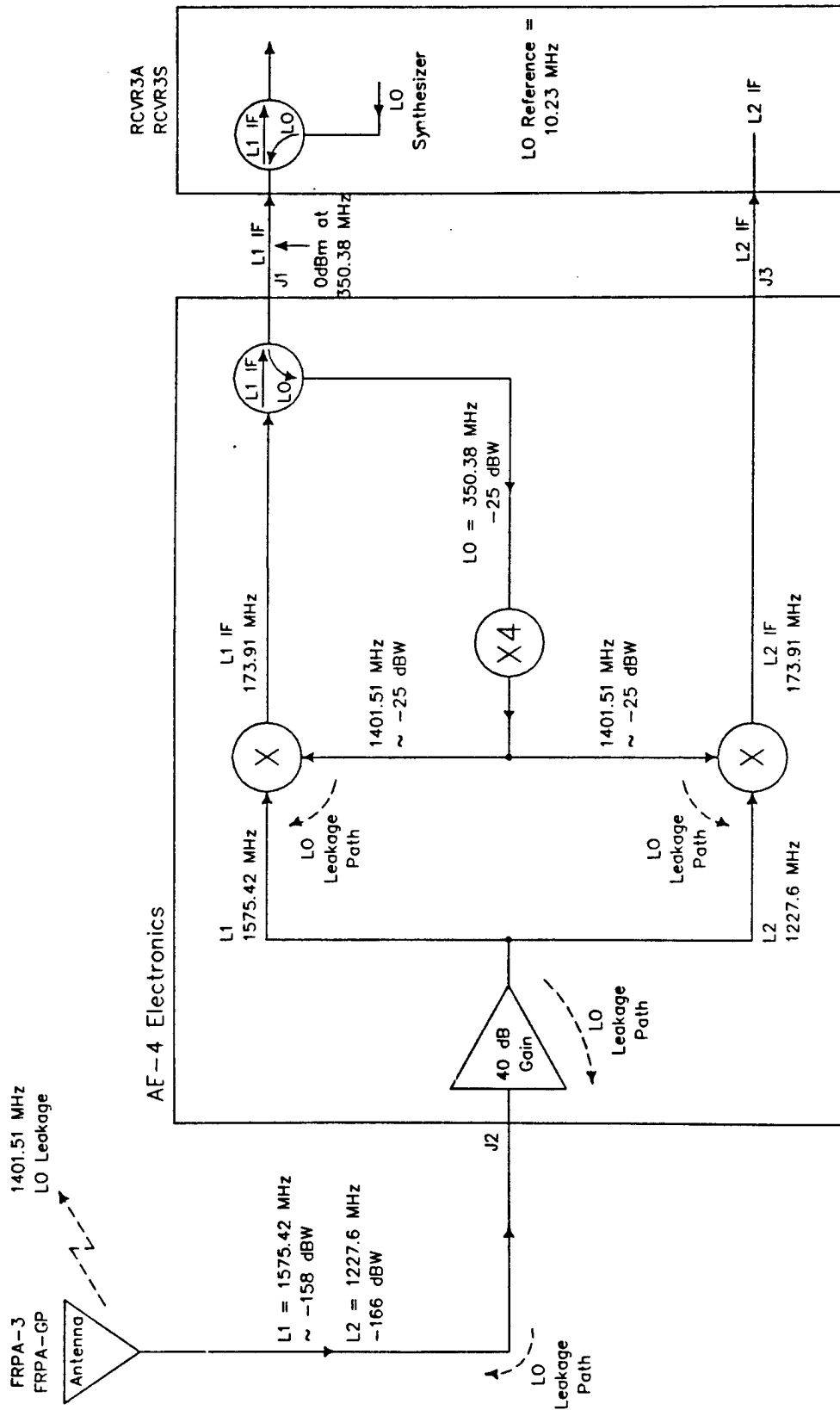


Figure 3-1. Rockwell/Collins UE RF/IF/LO architecture.

MIL-STD-461 CE06 specifications provide an upper bound on the allowable unintentional power levels which may reside at the GPS UE antenna terminal. Likewise, MIL-STD-461 RE02 specifications provide an upper bound on radiation from the GPS UE subsystem RF cables, case, and components. (NOTE: Radiation from the IF cables illustrated in Figure 3-1 are not tested as part of the standard Rockwell/Collins MIL-STD-461 verification process.) This assessment of interceptibility evaluates the impact of these "worst case" MIL-STD-461 specified levels, along with known levels which exist on the IF cables.

Strict quality control must be utilized in the GPS UE installation process such that RF and IF cable/connector shield integrity is verified and maintained. Shield damage or shielding deficiencies could impact the detectability of unintentional emissions, and this impact should be evaluated.

From the standpoint of Interceptibility, one must be concerned if these unintentional emissions are of high enough a level to be detected and utilized to assist hostile jamming efforts.

It is important to note that from a practical standpoint, the LO emissions from the GPS UE are likely to be minute compared to other radar and communications emissions from the same platform.

Limits on radiated emissions and testing scenarios are specified by MIL-STD-461 and MIL-STD-462, respectively. Associated tests generally involve: 1) directly measuring the power level of spurious leakage components on interconnecting leads, and 2) performing near-field antenna measurements in a closed chamber environment to determine radiated component field levels.

Unfortunately, these tests do not always give adequate indication of the radiated power levels in the far-field. From the standpoint of Interceptibility, it must be determined if these far-field radiated levels are high enough to allow for intercept and direction of jamming resources, and determine 'Worst Case' limits on Interceptibility.

In the flavor of the DVAL Interceptibility Methodology, the following section evaluates the potential impact of the above mentioned unintentional emissions.

3.3 Evaluation of Unintentional Emissions

This section focuses on the determination of potential unintentional emission worst case radiated power levels.

Lack of far-field measurement test data motivates simple calculations to assess Interceptibility owing to unintentional emissions. These calculations have been performed in the following fashion:

- . Worst Case allowable MIL-STD-461 emission levels have been utilized for the unintentional emissions of interest.
- . These MIL-STD-461 levels have been extrapolated to the far-field, providing for a worst case approximate potential far-field radiated level.
- . Based on these potential far-field levels, link analyses have been performed in an effort to determine at what maximum ranges intercept could potentially occur.

Several major obstacles exist regarding this analysis which include:

- . No data exists related to far-field emission levels.
- . Capability to make valid far-field assumptions based on MIL-STD-461 specifications is limited.
- . Capability to accurately determine the degradation in shielding effectiveness from a multitude of cable shielding deficiencies and other shielding sources does not exist.

The various allowable emission levels specified in MIL-STD-461, along with known power levels existing within the Rockwell/Collins GPS UE have been used to assist this analysis of potential radiated power levels.

3.3.1 Evaluation of 1401.52 MHz LO Emission Level

To begin this evaluation, worst case MIL-STD-461B (surface ships) CE06 limits have been utilized. These CE06 limits imply that conducted emissions in excess of 34 dB μ V (narrowband) shall not appear at the test sample's antenna terminals.

Assuming a 50 ohm impedance for the RF cable between the GPS antenna and the AE-4 Electronics assembly, the specified CE06 upper limit implies a worst case power level of -73 dBm at 1401.52 MHz.

CE06 Level on RF Cable: -73 dBm (34 dB μ V) (1)

Obviously, the amount of this 'worst case' potential power that could be radiated depends on a number of factors which include cable length, cable shielding effectiveness, other shielding, etc. Link analysis performed in a later section will take these factors into account.

MIL-STD-461B REO2 limits for narrowband emissions illustrated in Figure 3-2 indicate that at 1401.52 MHz, field emissions must be limited to 55 dB μ V/meter. It should be noted that this narrowband REO2 limit is based on a near-field measurement performed at a distance of 1 meter. Relating the measured near-field strength to the potential far-field strength can prove to be a complex exercise, so efforts have been made to develop approximate bounds on the maximum potential far-field level.

If simplifying assumptions are utilized, an indication of the potential far-field strength [or alternatively the potential EIRP (Effective Isotropic Radiated Power) generated from the unintentional emitter] can be approximated in the upper bound sense.

At 1401.52 MHz, the allowable MIL-STD-461B REO2 narrowband emission electric field strength (E Volts/m) measured at 1 meter is specified as:

$$\begin{aligned} E &= 55 \text{ dB}\mu\text{V/m} \\ &= 562 \mu\text{V/m} \end{aligned} \tag{2}$$

Assuming a free space impedance of 377 ohms, the approximated power density (P_d) associated with 562 μ V/m is given by:

$$\begin{aligned} P_d &= E^2/377 \\ &= 837.78 \times 10^{-12} \text{ (W/m}^2\text{)} \end{aligned} \tag{3}$$

Utilizing the MIL-STD-462 separation distance of 1 meter, and the value of P_d expressed in Equation (3), the potential EIRP level is given as:

$$\text{REO2 EIRP of Unintentional Emission: } -49.77 \text{ dBm} \tag{4}$$

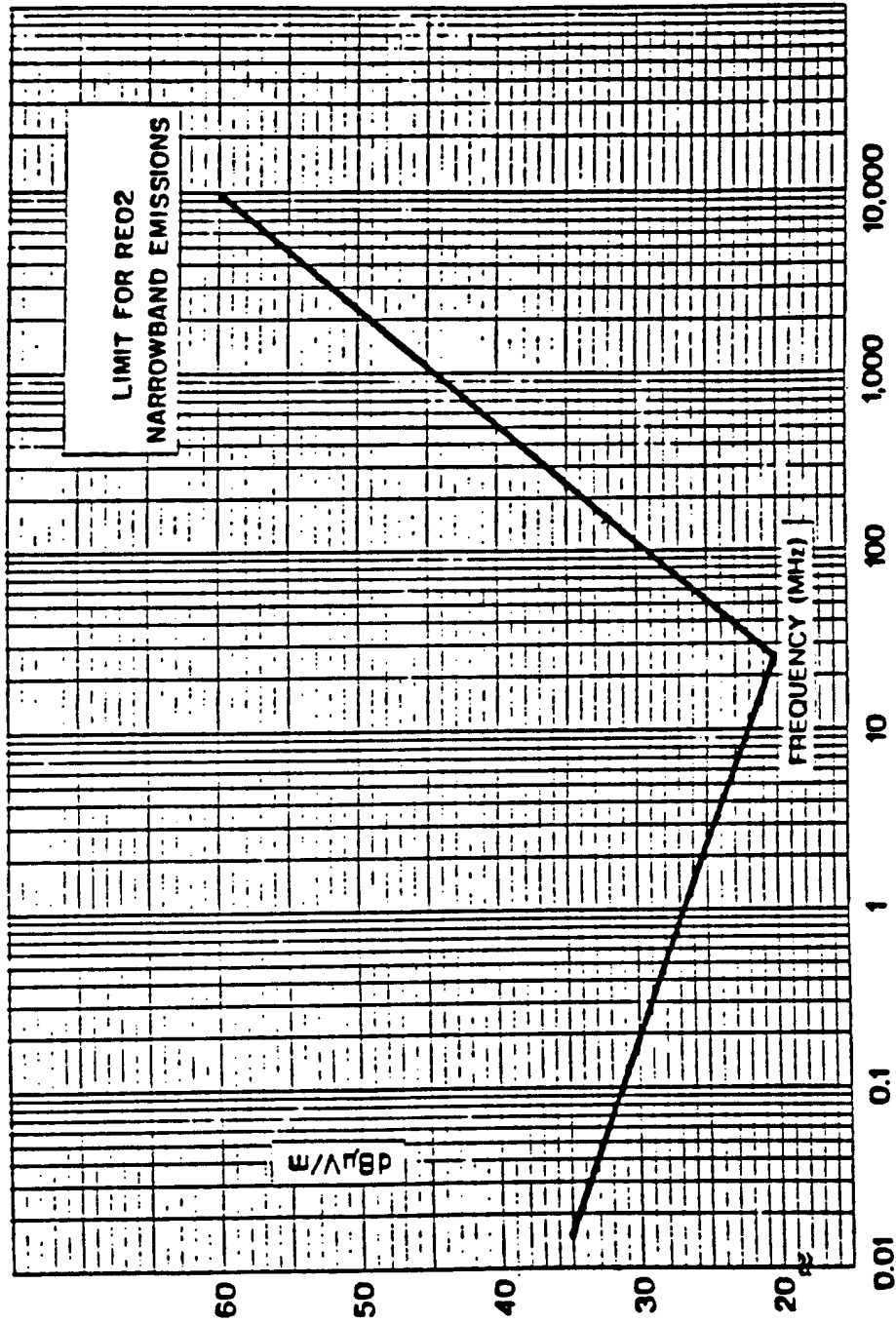


Figure 3-2. Limit for RE02 narrowband emissions.

In this calculation, the REO2 field emission limit at 1401.52 MHz has been converted to an approximate EIRP level utilizing Far Field assumptions. This level can now be used to perform a 'worst case' link analysis in an effort to assess the potential Interceptability of the GPS UE. In this sense, 'worst case' is defined based on the following assumptions:

- (1) The GPS UE emits at the specified REO2 level. (Conversations with Rockwell/Collins indicate that the GPS UE emits below the REO2 specified levels.)
- (2) The far field assumptions invoked in the derivation of the radiated power level (EIRP) constitute an approximate upper bound on the actual potential level.

In summary, with no actual measured far-field data on the potential 1401.52 MHz LO leakage component, the preceding assumed values in Equations (1) and (4) have been utilized to assess the Interceptability potential of the GPS UE in the worst case sense. The approximated EIRP is a convenient quantity used in standard link analysis calculations which follow in a later section.

3.3.2 Evaluation of the 350.38 MHz LO Emission Level

The 350.38 MHz LO, used in the derivation of the 1401.52 MHz LO, is transferred to the AE-4 downconverter from the RCVR3A (or RCVR3S) module via the L1 IF cable. The actual average power level of the 350.38 MHz LO component on the IF cable is 0 dBm.

Actual Level on IF Cable: 0 dBm (5)

The MIL-STD-461B limit for REO2 narrowband emission at 350.38 MHz is 39 dB μ V/m. Performing an analysis of the potential EIRP as illustrated in Equations (2)-(4), the potential 'worst case' EIRP at 350.38 MHz is given as:

RE02 EIRP of Unintentional Emission: -65.77 dBm (6)

3.3.3 Evaluation of the 10.23 MHz LO Emission Level

The 10.23 MHz LO resides in the RCVR3A (or RCVR3S) receiver module. All UE LO's are derived from this 10.23 MHz reference. In addition to driving all system LO's, this reference is utilized to drive the P and C/A Code clocks, therefore, there is a potential for this 10.23 MHz signal to be rich in even order and odd order harmonics.

Referring to the MIL-STD-461B RE02 limits for narrowband emissions, the specified limit at 10.23 MHz is 22 dB μ V/m.

Performing the approximate analysis as presented in Equations (2)-(4), the potential allowable EIRP at 10.23 MHz is given as:

RE02 EIRP of Unintentional Emission: -82.77 dBm (7)

4.0 ANALYSIS OF GPS RECEIVER INTERCEPTIBILITY

4.1 Feasibility of Detection

This section discusses the feasibility of detecting the GPS UE based on the calculated potential worst case EIRP levels of unintentional emitters discussed in the previous section.

For all three unintentional frequencies of interest, the following analysis has been used to determine the maximum range that a hypothetical intercept receiver must be from the GPS UE in order to effectively exploit unintentional emissions from the GPS UE.

The following link equation [1] will be used to assess the feasibility of detection:

$$\left(\frac{C}{N}\right) \text{ dB} = 10\log(\text{EIRP}) - 20\log(4\pi r/\lambda) + 10\log(G_R/T) - 10\log(k) - 10\log(\text{BW}) \quad (8)$$

where,

C/N = Carrier power to Noise power Ratio (CNR)

λ = $c/f = (2.99 \times 10^8 \text{ m/s}) / \text{frequency (Hz)} = \text{wavelength}$

G_R/T = intercept receiver figure of merit

k = Boltzman's constant

BW = intercept receiver effective noise bandwidth

EIRP = assumed potential radiated power from GPS UE

r = maximum intercept receiver separation distance for the specified received C/N , receiver G_R/T , and approximated potential emission EIRP

For the purposes of this analysis, the following additional assumptions are made:

- (1) Atmospheric losses are assumed negligible.

- (2) The hypothetical intercept receiver effective noise bandwidth is 2 kHz.

The following Tables 4.1 through 4.3 summarize the maximum distances at which the specified hypothetical intercept receivers will be able to perform a detection.

Table 4.1 summarizes the range requirements for an intercept receiver with the specified G_R/T figure of merit, a 2 KHz effective receiver noise bandwidth, and the specified received CNR for detection of the 1401.52 MHz LO emission. Two values of CNR (i.e. 5 and 20 dB) are utilized. In the general sense, if the intercept receiver receives the unintentional emission at a CNR of 20 dB, then the probability of detection is obviously very high. Likewise, at a received CNR of 5 dB, the probability of detection is low. The values of G_R/T (figure of merit) used correspond to a fairly high quality intercept receiver. The calculated MIL-STD-461B GPS UE 1401.52 MHz emission EIRP of -49.78 dBm (-79.78 dBW) was utilized in this link analysis. Note that based on the specified parameters, the hypothetical intercept receiver could be as far away as 10 km (line-of-sight) for a high probability of detection, ignoring the effects of atmospheric attenuation.

As specified in Equation (1), the potential MIL-STD-461B CE06 level of the 1401.52 MHz signal on the RF antenna cable may never exceed -73 dBm (-103 dBW). Assuming that the cable and associated filtering provides for a 'worst case' 3 dB attenuation, then the potential EIRP level of -106 dBW implies that in the 'worst case' sense, detection could be possible at ranges of up to 0.5 km, as illustrated in Table 4.1. In a practical sense, cable shielding deficiencies would in general result in a worst case 30 dB attenuation, instead of the 3 dB attenuation used in this analysis. Therefore, intercept based on this worst case CE06 level is virtually impossible.

TABLE 4.1

LINK ANALYSIS FOR RECEPTION OF 1401.52 MHZ LO

LO EIRP	Required CNR	G_r/T	Maximum Potential Range
-80 dBW	5 dB	20 dB	58.0 km
-80 dBW	20 dB	20 dB	10.0 km
-106 dBW	5 dB	20 dB	2.9 km
-106 dBW	20 dB	20 dB	.5 km

TABLE 4.2

LINK ANALYSIS FOR RECEPTION OF 350.38 MHZ LO

LO EIRP	Required CNR	G_r/T	Maximum Potential Range
-95.77 dBW	5 dB	10 dB	12.0 km
-95.77 dBW	20 dB	10 dB	2.1 km
-110 dBW	5 dB	10 dB	2.3 km
-110 dBW	20 dB	10 dB	.4 km
-110 dBW	20 dB	20 dB	1.3 km

TABLE 4.3

LINK ANALYSIS FOR RECEPTION OF 10.23 MHZ LO

LO EIRP	Required CNR	G_r/T	Maximum Potential Range
-113 dBW	20 dB	10 dB	10.0 km
-113 dBW	5 dB	-10 dB	5.6 km
-113 dBW	20 dB	-10 dB	1.0 km

In summary, this analysis indicates that based on the allowable 'worst case' MIL-STD-461 levels, a very slight potential exists for the detection of the 1401.52 MHz LO emission. Care must be taken to assure that this unintentional LO emission is appropriately attenuated by proper cable shielding, and that system filtering (i.e. GPS UE receive antenna filtering) also provides for adequate attenuation. In a more practical sense, for receivers which emit well below the allowed RE02 level, detection of this emission could be feasible only at very short ranges, implying that there is a very low risk of Interceptibility based on this emission.

Table 4.2 summarizes intercept receiver range requirements for reception of the unintentional 350.38 MHz LO emission. Equation (6) indicates that the potential EIRP of the 350.38 MHz LO may never exceed -95.77 dBW. Based on this potential power level, intercept could take place at ranges up to approximately 2.1 km. Note that at this frequency, 'line of sight' is not required for detection.

Equation (5) indicates that the power level on the GPS UE IF cable is approximately 0 dBm (-30 dBW). Assuming an IF cable radiated power shielding attenuation of 80 dB, the potential EIRP of the 350.38 MHz signal could be approximately -110 dBW implying that high probability detection could not occur at ranges greater than .5 km.

Table 4.3 summarizes intercept receiver range requirements for the potential unintentional 10.23 MHz emission. As previously discussed, this signal has the potential to be rich in odd and even order harmonics. If it is assumed that the harmonics may radiate at the same specified EIRP level as the fundamental frequency, than obviously detection ranges will be appropriately increased.

In conversations with agencies responsible for performing EMI/EMC testing of the GPS UE (i.e. NADC, GTRI), it has been reported that the GPS UE has been found to adversely affect other communication systems located on the same platform at intervals of 10.23 MHz in the HF, UHF, and VHF regions. Although this does not explicitly imply that high far-field radiation levels exist at multiples of 10.23 MHz, with the absence of any far-field measured data, these actual far-field levels are currently unknown.

The simple link analysis formula presented in Equation (8) does not take into account the effects of HF propagation phenomena such as ionospheric reflection. With this in mind, it is noted in Table 4.3 that detection can not take place at ranges greater than 1 km. Therefore, based on this analysis, the probability of Intercept of the 10.23 MHz LO and its harmonics is low.

5.0 CONCLUSIONS

Conversations with Rockwell/Collins engineers have indicated that the actual emission levels of the GPS UE fall well below the allowable MIL-STD-461 specification. Telephone references have been made regarding the following Rockwell/Collins reports: 1) EMI Test Report for GPS RCVR3A, 2) EMI Test Report for GPS RCVR3S, and 3) AE-4 EMI Test Report.

Unfortunately, these reports could not be obtained in time to be reviewed and discussed in the current document. They will be reviewed when received at Georgia Tech. From extensive interactions with Rockwell-Collins personnel it is not expected that they will result in a different perspective from that presented here.

As supported by the calculations presented in this report, the potential for interceptibility of the GPS UE is very low. It should be pointed out that far-field measurements were not performed as part of the routine Rockwell/Collins testing procedures. The link calculations presented in this report are based on approximate near-field to far-field worst case translations.

Even though ideal propagation conditions are implicit in these calculations, the results do not indicate detectibilities of great concern. In consideration of the additional facts that the calculations are based on the maximum allowable radiated signals (according to emission specifications) and the emissions are reported to be well below spec, there is little reason for major concern relative to the interceptibility of unintended emissions from the GPS receiver.

From a practical standpoint, standard emissions from ship-based platforms should lead to much higher probabilities of detectibility than unintentional emissions from the GPS UE.

Figure 5.1 illustrates a comparison of 'broadband' REO2 levels versus the specified EMCON (EMission CONTROL) level at 1 nautical mile. As shown, near-field REO2 levels (measured at 1 meter) extrapolated out to 1 nautical mile fall well below the EMCON level.

If planned and on-going EMC/EMI tests result in field strengths higher than those expected, it may be necessary to re-evaluate the situation relative to Interceptibility. Currently, however, the calculations and discussions presented in this report indicate that the probability of Intercept is low. Accordingly, far-field measurements of Interceptibility are not recommended.

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- [1] Feher, Kamilo; Digital Communications, Satellite/Earth Station Engineering, Prentice Hall, 1983.

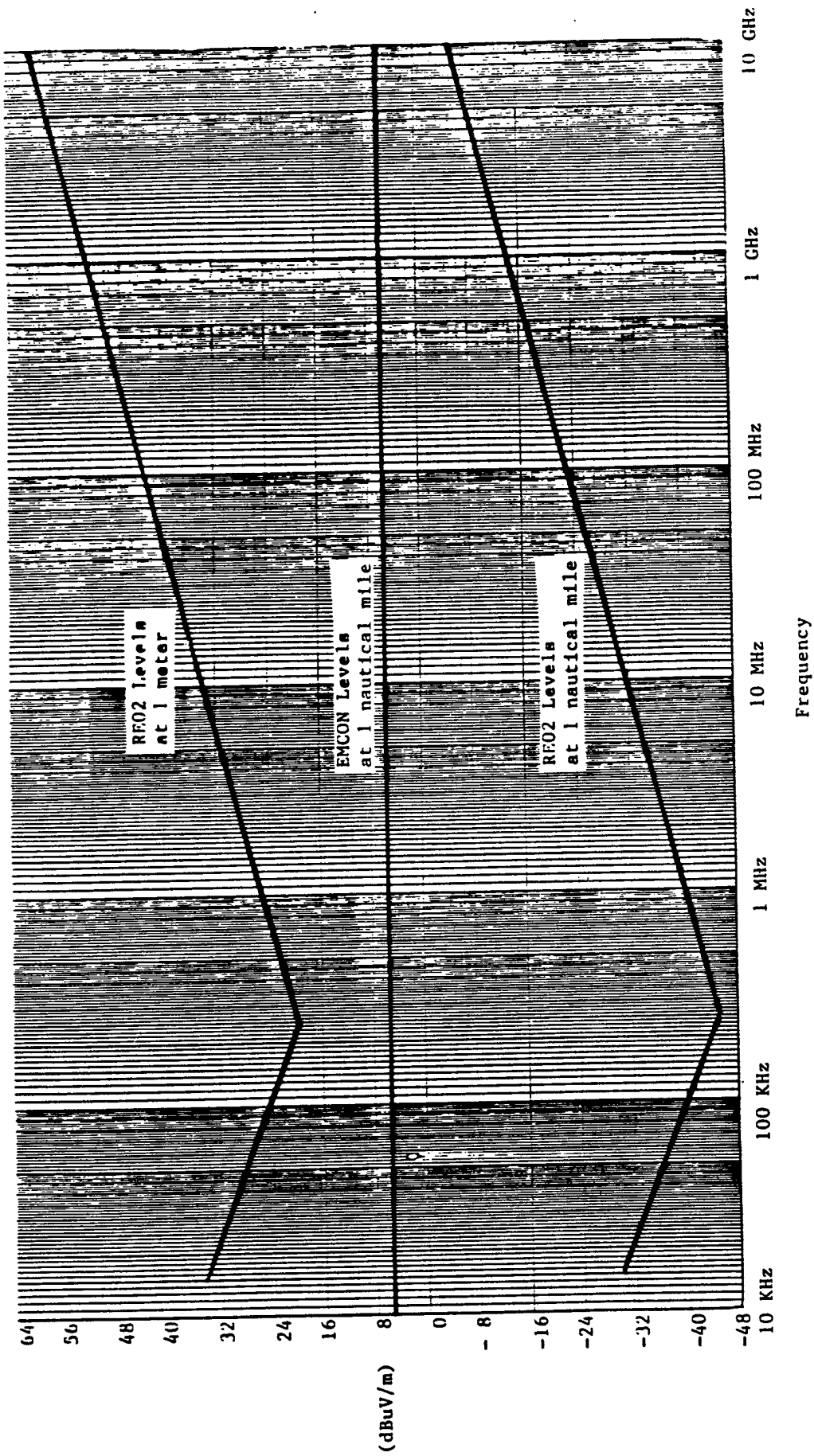


Figure 5-1. Comparison of RE02 test levels vs. EMCON levels.