

WIDEBAND GLOBAL SATCOM (WGS) EARTH TERMINAL INTEROPERABILITY DEMONSTRATIONS

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ABSTRACT

This paper describes the earth terminal (ET) interoperability demonstrations that were conducted with the Wideband Global SATCOM (WGS) Block I payload engineering model testbed (PEMT) in the factory, and with the WGS-1 satellite on orbit. In June 2005, during the course of initial interoperability demonstrations with the PEMT, the results showed that, although it met the integrated phase noise specification, the payload phase noise power spectral density (PSD) was sufficiently elevated in some frequency offset ranges to cause unacceptable negative impact on communications performance for 8-PSK and 16-QAM waveforms of interest to DoD. Further testing revealed that the high phase noise originated in some of the payload's synthesized reference generators (SRGs). Boeing and the Government ultimately determined that the integrated phase noise specification that was levied on the payload was not sufficient to ensure good performance for higher order modulation schemes, and that a mask would need to be imposed on the payload's phase noise PSD. Boeing modified the SRGs on all Block I satellites prior to launch in order to meet this new phase noise mask. On June 6, 2006, interoperability testing recommenced with an improved SRG installed in the WGS PEMT. Further testing, concluded in November 2006, showed that the reduced phase noise of the modified SRG improved communications performance to satisfactory levels. WGS-1 was launched on October 10, 2007 with the improved SRGs. The WGS-1 On-Orbit Terminal Interoperability Demonstration (OOTID) was successfully concluded on January 16, 2008. The OOTID, which employed the same ETs used during the PEMT tests, confirmed that the communications performance improvements are also present in the operational satellite. WGS Block II phase noise performance is expected to be even better than Block I as a result of a decision to implement a new SRG design for these follow-on satellites.

INTRODUCTION

The WGS Program brings a new generation of flexible capability and increased capacity to MILSATCOM. Each WGS satellite provides as much capacity as the entire constellation of the predecessor Defense Satellite Communications System (DSCS) satellites. DSCS uses X-band. WGS uses both X- and Ka-band and allows cross-

banding between the two. Roughly 60% of WGS capacity is in Ka-band. X-band is less susceptible to weather fades, but Ka-band can offer electromagnetic compatibility (EMC) advantages over X-band in some applications.

RISK REDUCTION APPROACH

To address risk, Boeing and the Wideband SATCOM Group (MCWG) of the MILSATCOM Systems Wing (MCSW) at the Space and Missile Systems Center (SMC), Los Angeles AFB, CA, decided early on to demonstrate earth terminal (ET) interoperability with the WGS Block I payload prior to the first launch. The enabler for this work was an engineering model of the WGS Block I communications payload that was built by Boeing with flight-like hardware. In most cases, the hardware used in the WGS payload engineering model testbed (PEMT) consisted of early serial numbers of identical-to-flight units. In other words, the only thing preventing one from calling the bulk of the PEMT hardware "flight hardware" was that it simply wasn't going to fly. Actual flight hardware components and subsystems (e.g., synthesized reference generators) could be (and were) inserted into the PEMT for performance characterization measurements.

Two ETs were used in the interoperability demonstrations with the PEMT and subsequently with the first Block I space vehicle, WGS-1. These were (1) an AN/TSC-93D X-band terminal provided by the US Army's PM WIN-T (Program Manager, Warfighter Information Network - Tactical), and (2) the 2.4-meter diameter SSC Pacific Commercial-off-the-Shelf (COTS) Ka-Band Transportable Terminal (SCKaTT). Both ETs were extensively characterized prior to the interoperability demonstrations and shown to be compliant with MIL-STD-188-164A [1]. Interoperability with the PEMT (and then with WGS-1) was demonstrated by collecting communications performance curves, i.e., bit-error ratio (BER) versus the energy per information bit to thermal noise power spectral density ratio (E_b/N_0), for a number of test cases that were distinguished by various information rates, modulation formats, forward error correction (FEC) coding methods, and different paths through the payload. Measures of communications performance derived from these curves quantified the impacts of the WGS payload on end-users' signals.

The PEMT demonstrations were accomplished in two phases, which have come to be known as “PEMT I” (May through August 2005) and “PEMT II” (June 6 through November 15, 2006). The PEMT I demonstrations uncovered the fact that although the payload met its integrated phase noise specification, the phase noise power spectral density (PSD) it imposed on communications signals was sufficiently elevated in some frequency offset ranges to cause unacceptable negative impact on communications performance for 8-PSK and 16-QAM waveforms of interest to DoD. Further testing revealed that the high phase noise originated in some of the payload’s synthesized reference generators (SRGs). Boeing and the Government ultimately determined that the integrated phase noise specification that was levied on the payload was not sufficient to ensure good performance for higher order modulation schemes, and that a mask would need to be imposed on the payload’s phase noise PSD. Boeing modified the SRGs on all Block I satellites prior to launch in order to meet this new phase noise mask. The PEMT II demonstrations showed that Boeing’s enhancements to the phase noise performance of the WGS Block I SRG significantly improved the communications performance of the payload over that which was observed during PEMT I for higher-order modulations. The OOTID, which employed the same two earth terminals used during PEMT I and PEMT II, confirmed that these improvements were also observed on-orbit in the operational satellite.

The experience outlined in the previous paragraph clearly demonstrated the value of constructing the PEMT with flight-like hardware and using it to demonstrate interoperability with representative wideband ETs. The remainder of this paper describes the setups, methods and some of the results of the interoperability demonstrations. Archival descriptions of PEMT II and the WGS-1 OOTID are given in [2] and [3], respectively. Distribution of these technical reports is limited to the DoD and U.S. DoD contractors that support the WGS program.

INTEROPERABILITY DEMONSTRATION SETUPS

Figure 1 shows the in-factory configuration used for the interoperability demonstrations with the PEMT, both in PEMT I and in PEMT II. There were two simultaneous simplex links. One ET transmitted while both ETs received. The transmit powers of the ET high power amplifier (HPA) and the PEMT downlink HPAs were held constant. Each ET HPA was operated at a representative high-power level into a dummy load via a coupler that provided a medium-power sample of the uplink signal. The E_b/N_0 on each link was independently controlled by a dedicated radio frequency (RF) attenuator operating on the downlink. This setup allowed two test cases to be run simultaneously. All connections were made with cables in the factory, except for a 21-foot section of WR34

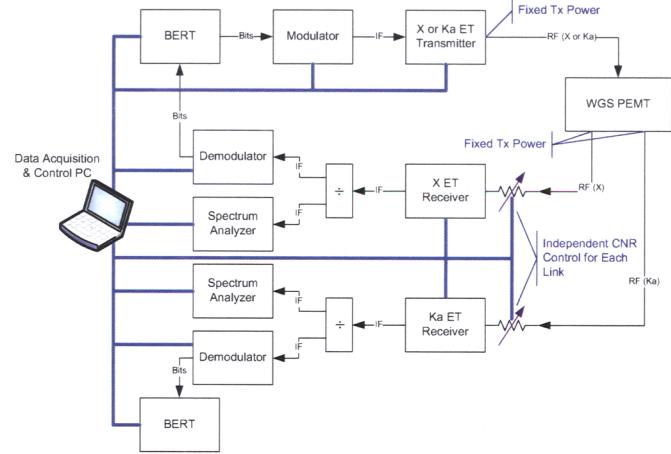


Figure 1. WGS PEMT I and PEMT II setup.

waveguide used to support most of the Ka-band uplink signal path from the SCKaTT to the PEMT. The intermediate frequency (IF) signal destined for each demodulator was split so that it could be simultaneously monitored on a spectrum analyzer to measure carrier-to-noise ratio (CNR), C/N . The measurement made directly by the spectrum analyzer was $(C+N)/N$, which was converted to C/N and E_b/N_0 as follows.

$$C/N = ((C + N)/N) - 1$$

$$E_b/N_0 = (R_S/R) \times (C/N)$$

where R_S is the modulation-symbol rate and R is the information-bit rate.

Figure 2 presents the OOTID setup, which mimics the PEMT setup shown in Figure 1. This setup also maintained constant operating points for the carrier under test at the ET HPA and the WGS-1 satellite downlink HPAs.

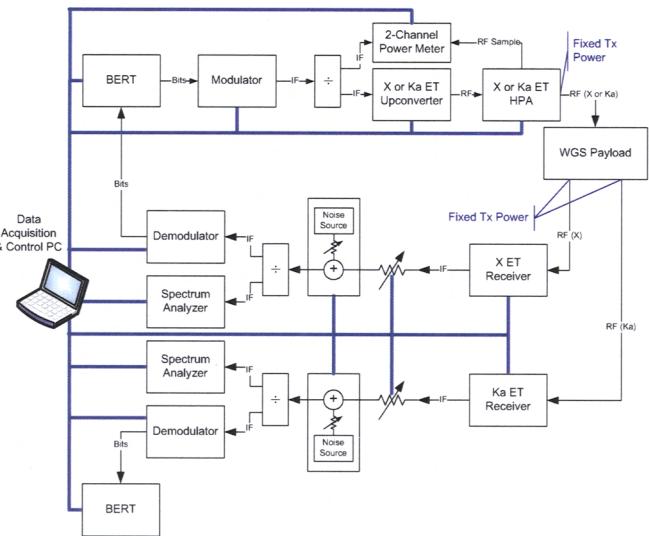


Figure 2. WGS-1 OOTID setup.

The E_b/N_0 values on each link were independently controlled by a combination of (1) attenuating and (2) adding thermal noise to the received IF signal. This approach was preferable to using RF attenuators prior to the ET low noise amplifiers because it did not negatively impact G/T . The levels provided by the noise generators in Figure 2 were determined prior to each OOTID test run and left fixed. Subsequent E_b/N_0 changes were accomplished by adjusting the IF attenuators only. The transmit operating point for each ET was ~ 5 dB backed off from the 1-dB compression point.

DEMONSTRATION WAVEFORMS

Table 1 describes six of the waveforms used during the interoperability demonstrations. RS(204, 187) was used instead of the standard RS(204, 188) with the Digital Video Broadcast (DVB) waveforms because when set up for RS(204, 188), the SDM-2020M modulator inserts a DVB framing bit into the output bit stream. This is necessary when communicating with other DVB devices. But the Fireberd 6000 BERTs used in the setup were not DVB devices. From the perspective of the receiving BERT, the framing bit is an extra bit that is not part of the PN sequence. When the framing bit is present, the receiving BERT cannot synchronize to the PN sequence. Using RS(204, 187) instead of RS(204, 188) removes the DVB framing bit so the receiving BERT can synchronize to the PN sequence.

Table 1. Interoperability demonstration waveforms.

R (kbps)	Mod.	FEC	Standards	Modems
256	8-PSK	2/3 PTCM, RS(219, 201), Intlv Depth 8	IESS-310	SLM-7650
1,544	16-QAM	7/8 PTCM, RS(219, 201), Intlv Depth 8	MIL-STD-188-165A, IESS-310	SLM-7650
8,448	8-PSK	2/3 PTCM, RS(219, 201), Intlv Depth 8	MIL-STD-188-165A, IESS-310	SLM-7650
23,500	QPSK	2/3 CC, RS(204, 187), Intlv Depth 12	EN 300 421 (DVB)	SDM-2020M/D
50,000	8-PSK	5/6 PTCM, RS(204, 187), Intlv Depth 12	EN 301 210 (DVB)	SDM-2020M/D
50,000	16-QAM	7/8 PTCM, RS(204, 187), Intlv Depth 12	EN 301 210 (DVB)	SDM-2020M/D

MEASURES OF

COMMUNICATIONS PERFORMANCE

Two measures were used for evaluating communication performance curves: *waveform implementation loss* (WIL) and *flare*. Implementation loss is defined as the

difference between the theoretical demodulation performance and the performance of the actual demodulator at a target BER. The target BER values used in the demonstrations depended on the information-bit rate, R as follows.

- $R \leq 64$ kbps: Target BER = 10^{-6}
- $64 \text{ kbps} < R \leq 256$ kbps: Target BER = 10^{-7}
- $R > 256$ kbps: Target BER = 10^{-8}

Since implementation loss depends on the modulation format, FEC coding scheme, and information rate of the communications waveform, the team adopted the phrase waveform implementation loss. Figure 3 illustrates WIL.

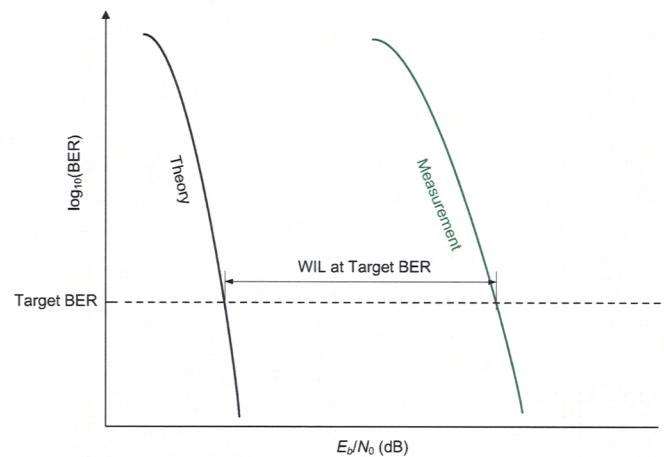


Figure 3. WIL.

Implementation loss is a well known metric, but flare does not seem to be widely used for assessing communications performance curves. We define flare as the dB change in the amount of E_b/N_0 -increase required to reduce the BER by one power of 10 in the measured performance curve as compared to the theoretical performance curve in the vicinity of the target BER:

$$\text{Flare} \triangleq \left(\frac{d(E_b/N_0)}{d(\log_{10}(\text{BER}))} \right)_{\text{Theory}} - \left(\frac{d(E_b/N_0)}{d(\log_{10}(\text{BER}))} \right)_{\text{Measurement}}$$

Since $d(\log_{10}(\text{BER})) = -1$,

$$\text{Flare} = d(E_b/N_0)_{\text{Measurement}} - d(E_b/N_0)_{\text{Theory}}.$$

- Flare > 0 implies a greater increase in E_b/N_0 is required to achieve the power-of-10 decrease in BER than according to theory. The smaller the flare, the better.
- Flare = 0 is rarely achieved, even in IF loopback.
- Flare < 0 is sometimes observed due to experimental error.

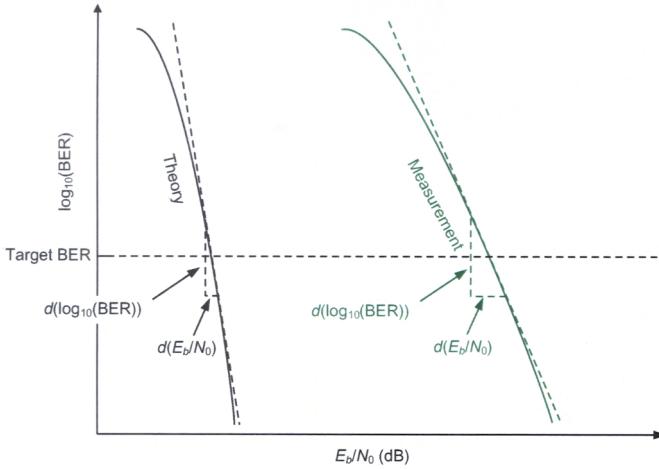


Figure 4. Flare.

Flare is useful when communications performance is dominated by a non-additive noise source (e.g., phase noise) at high E_b/N_0 . The presence of this other noise source elevates the amount of E_b/N_0 increase required to reduce the BER by an order of magnitude compared to theoretical performance. This causes a communications performance curve to have a “flared” appearance. Figure 4 illustrates flare.

DEMONSTRATION RESULTS OVERVIEW

Figure 5 presents communications performance curves collected during PEMT I, PEMT II, and the OOTID using the 50-Mbps, 8-PSK waveform described in Table 1. In these examples, the uplink was in X-band and the downlink was in Ka-band (cross-banding). The leftmost curve represents theoretical (best possible) communications performance. It was provided by The Aerospace Corporation’s Mark Shane, Lamont Cooper, and Dean Sklar. The blue and red curves (2nd and 3rd leftmost, respectively) show IF and RF loopback measurements, respectively. The IF measurement was made with the SDM-2020M modulator transmitting to the SDM-2020D demodulator without any ET hardware in the signal path. The RF loopback measurement involved a crossband loopback test translator (CBLTT) designed and constructed by SSC Pacific personnel at the suggestion of The Aerospace Corporation’s Bob Dybdal. The CBLTT enabled the collection of RF loopback baseline performance curves for all four possible uplink/downlink RF band combinations; its design is given in [2]. The brown (rightmost) performance curve exemplifies the poor communications performance uncovered in PEMT I for 8-PSK. The green (2nd rightmost) performance curve was measured during PEMT II; comparing it with the brown curve shows the degree of communications performance improvement achieved with the enhanced WGS Block I SRG. The WIL and flare performance measures improved

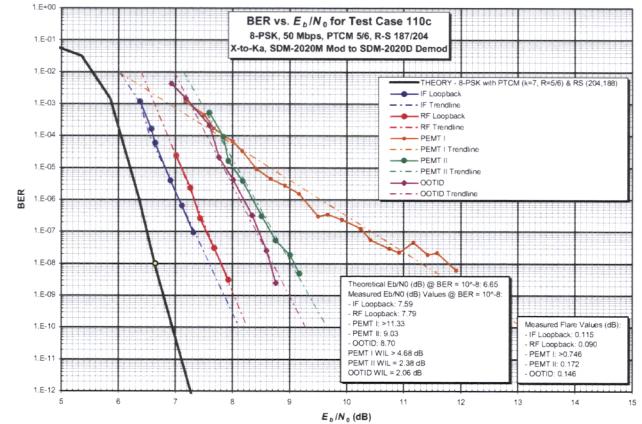


Figure 5. Example communications performance curves.

by more than 2.3 dB and 0.5 dB, respectively. Finally, the purple performance curve just to the left of the green one was measured during the OOTID. The on-orbit WIL and flare values in this case were roughly 0.3 dB and 0.03 dB better than those measured during PEMT II, respectively.

Figures 6 and 7 compare the WIL and flare values measured during PEMT II and the OOTID for all OOTID test cases for all the waveforms listed in Table 1. The up-link/downlink RF band combinations are indicated by the letter in the test case identifier as follows: a is X/X, b is Ka/Ka, c is X/Ka, and d is Ka/X. No clear OOTID versus PEMT II trend emerges from the comparisons. Sixteen (16) OOTID WIL values are greater than the corresponding PEMT II values. Twelve (12) PEMT II WIL values are greater than the corresponding OOTID values. Thirteen (13) OOTID flare values are greater than the corresponding PEMT II values. Fifteen (15) PEMT II flare values are greater than the corresponding OOTID values. Overall, WGS-1 communications performance was equivalent to that measured on the PEMT. Not surpris-

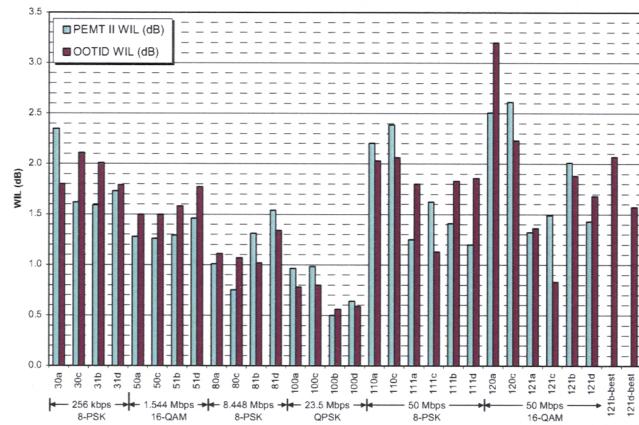


Figure 6. OOTID and PEMT II WIL values.

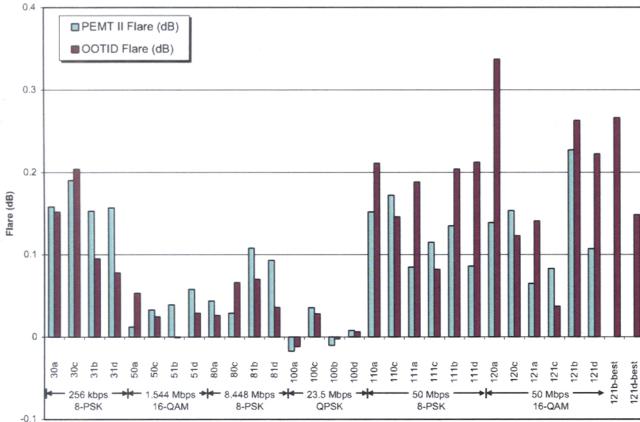


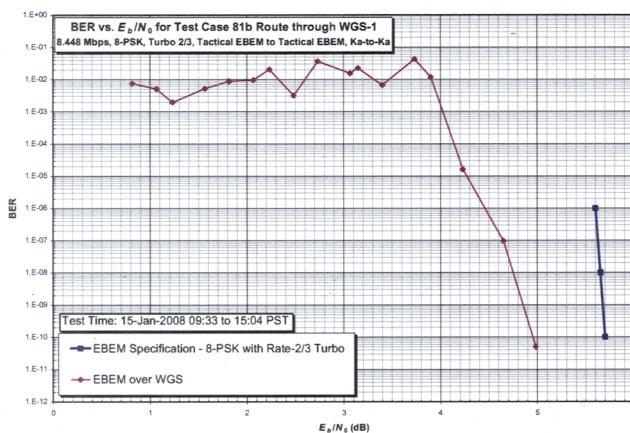
Figure 7. OOTID and PEMT II flare values.

ingly, the payload's impact on communications performance tends to be minimal for QPSK waveforms; all QPSK WIL measurements were less than 1 dB. Due to the improved SRGs, the payload's impacts on 8-PSK and 16-QAM communications performance are within acceptable limits. It should be noted that the results summarized in Figures 6 and 7 include the effects of the ETs on communications performance.

FIRST EBEM DEMONSTRATION VIA WGS-1

The Enhanced Bandwidth Efficient Modem (EBEM) is entering service throughout the DoD wideband SATCOM community. At the conclusion of the OOTID, the team conducted the first EBEM demonstrations over WGS-1 on January 15 and 16, 2008.

With a tactical variant EBEM in the SCKaTT and a strategic variant EBEM in the TSC-93D, the OOTID team demonstrated that WGS-1 supports better-than-specified communications performance with the EBEM's rate-2/3 turbo-coded, 8-PSK waveform operating at 8.448 Mbps



(16-APSK) waveform operating at 50 Mbps over a Ka/Ka link. This modulation format was introduced in [5] as an alternative to 16-QAM that has performance advantages when operating over non-linear channels. Figure 10 presents the 16-APSK communications performance curve measured on WGS-1. The measured E_b/N_0 at BER 10^{-8} was ~0.4 dB less than the specification.

CONCLUSIONS

The interoperability demonstrations conducted with the WBS Block I PEMT were effective in reducing risk, and they led directly to the superior communications performance for higher order modulations that has been delivered on orbit in WGS-1 by motivating the SRG upgrade. The results plotted in Figure 5 provide an example in which the upgraded SRG improved WIL and flare performance for 8-PSK (at BER = 10^{-8} and $R = 50$ Mbps) by more than 2.3 dB and 0.5 dB, respectively, when compared with the results obtained with the original SRG. WGS is now providing the Joint Warfighter with degrees of capacity and flexibility that are unprecedented in the history of MILSATCOM.

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- USAF Wideband SATCOM Group (MCWG), Los Angeles AFB, CA.

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