“A Regulatory Study and Recommendation for EIRP Spectral Density Requirement/Allowance for SOTM Terminals at Ka-Band on WGS System”

Lino Gonzalez
Chris McLain and
LinQuest Corporation

ABSTRACT

The Army’s WIN-T program is developing a new class of terminals for satellite on-the-move (SOTM) missions. The initial target satellites were commercial Ku-band satellites however, the ultimate goal is the Wideband Global System (WGS). WGS will consist of a geosynchronous constellation of at least six spacecrafts with X and Ka-band capable transponders. WGS is the newest department of defense (DOD) transponded satellite system. Earth Terminals (ET) that will utilize WGS will need to conform to MIL-STD-188-164A [1]. Currently, the DOD is in the process of updating MIL-STD-188-164A to add mobile satellite communications (SATCOM) requirements. One of the parameters that will be addressed is the off-axis equivalent isotropically radiated power (EIRP) Spectral Density (ESD) for ground mobile terminals. The ESD value is an extremely important parameter that will drive the achievable throughput, spectral efficiency, and adjacent satellite interference (ASI) levels of SOTM terminals and networks. The World Radio Regulations has designated the earth-to-space 30-31 GHz Ka-band, which is the band used by WGS, with a usage designation of co-primary fixed satellite (FSS) and mobile satellite service (MSS). This means that the same criteria used to analyze commercial Ku-band FSS is not applicable.

This paper looks at the system impacts of operating small mobile terminals at the 30-31 GHz Ka-band. It develops a methodology to analyze the overall performance impacts for SOTM networks, giving particular consideration to performance and the transmission impacts to adjacent satellite networks (ASN). The ASI will be quantified in terms of Equivalent Satellite Link Noise Temperature (ESLNT)[2] and its equivalent delta-T over T (delta-T/T). The analysis will examine ASI using the ESD limits provided by SMDC/ARSTRAT for WGS. Finally, based on this analysis, the paper will propose an off-axis ESD limits for inclusion in the update to MIL-STD-188-164B.

INTRODUCTION

The World Radio Regulations has designated the earth-to-space 30-31 GHz Ka-band, which is the band used by WGS, with a usage designation of co-primary fixed satellite (FSS) and mobile satellite service (MSS).

A frequency band can be allocated to one or more usage designations. Typically these usage designations have a primary or secondary status. The service with the primary status is given preference and is guaranteed interference protection from services with secondary status. A service with secondary status is not guaranteed interference protection from a primary status service. These are the circumstances in commercial Ku-band, with a designated FSS primary and MSS secondary. Due to this designation commercial Ku-band will never achieve reasonable spectral efficiencies for MSS networks. The 30-31 GHz Ka-band, has the potential to provide high throughput and high spectral efficiencies for both FSS and MSS by engineering interference levels so that both systems can coexist [3].

Inherent to the characteristics of a SOTM terminal is the large beamwidth produced by mechanically and electrically small directional antennas. The large antenna beamwidth may illuminate more than the just the intended satellite. The radiation intensity pattern caused by the large beamwidth can produce significant interference to adjacent satellites operating co-frequency, co-polarization in the Geostationary Satellite Orbit (GSO) arc.

Regulatory bodies have established interference limits to and from ASN for FSS networks[4]. However, little work has been done for dual primary FSS and MSS service on a single satellite. These networks will require special engineering to strike the correct balance of quasi ASI-free operations while maintaining practical spectral efficiency.
BACKGROUND

Generally, Figure 1 shows the interference scenario under evaluation. Although this figure shows one adjacent satellite, in practice all satellites within the field of view of the SOTM beamwidth must be considered. Note, in Figure 1, the red lines indicate unwanted transmission energy.

**FIGURE 1- Interference Scenario**

GSO communications satellites that use the commercial bands (i.e., Ku-band and C-band) are densely deployed in certain orbital locations. Commercial satellite operations in the continental United States (CONUS) are governed by the Federal Communications Commission (FCC) via performance standards for ET. The FCC’s antenna performance standards mandate that the gain of any antenna comply with a predefined envelope [5]. The envelope of the antenna gain in the commercial 14 GHz (Ku-Band) is given by equation 1.

\[
G(\theta) = \begin{cases} 
29 - 25 \log(\theta) & 0 \leq \theta \\
10 & 1 \leq \theta \leq 7 \\
1.86 - 25 \log(\theta) & 8 < \theta \\
-10 & 9 \leq \theta \leq 48 \\
\end{cases} \text{ dBi}
\]

Eq1

Where; the angle \( \theta \) is the angle in degrees from the axis of the main lobe, and dBi refers to dB relative to an isotropic radiator. The FCC also mandates the maximum power spectral density (PSD) level into a compliant antenna, the current value is -14dBW/4kHz. For non-compliant antennas this PSD level would need to be reduced dB for dB for the non-compliance levels. The combination of antenna gain envelope and the maximum PSD level into the antenna sets the maximum ET off-axis ESD level allowed by the FCC. The ESD operational level outside CONUS (OCONUS) is ruled by the International Telecommunication Union (ITU).

While limits exist for the commercial Ka-band below 30GHz neither the FCC nor the ITU specify ESD limits for the WGS Ka-Band frequencies above 30GHz. However, the performance requirements for US Military use of X-band are codified in MIL-STD-188-164A.

The ESD limit specified in MIL-STD-188-164A is:

\[
ESD(\theta) = \begin{cases} 
0.99 - 0.99 \log(\theta) & 0 < \theta \leq 1.1 \\
-2.7 & 1.1 < \theta \leq 1.5 \\
1.78 - 25 \log(\theta) & 1.5 < \theta \leq 48 \\
-40.2 & 48 < \theta \leq 180 \\
\end{cases} \text{ dBW/Hz}
\]

Eq2

Figure 2 compares the ESD envelopes of X-band, the ARSTRAT WGS Ka-band filing KA3, and commercial Ku-band as specified in ITU-R S.728 [6]. Note that the MIL-STD level and the ARSTRAT filing have similar shape and levels but are significantly higher than the commercial Ku-band limits for FSS networks.

**FIGURE 2-X, Ka, Ku-Band ESD Envelopes**

By using the current “KA3” ARSTRAT filed envelop together with a typical equivalent 18 inch gimbaled SOTM aperture with a 1 dB rms pointing loss\(^1\) the maximum allowable boresight ESD can be calculated as shown in Figure 3.

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\(^1\) The 1 dB pointing loss is a product WIN-T performance requirement. Note pointing accuracy of the antenna has significant impacts on cost, size, weight, power and reliability.
FIGURE 3- Maximum Boresight ESD

The maximum boresight ESD must be limited to -3.9dBW/Hz for this 18 inch antenna and pointing system accuracy to meet the ARSTRAT limit as shown in Figure 3. At a boresight ESD of -3.9dBW/Hz, this antenna pattern would radiate -19.2dBW/Hz at 2 degrees from boresight. The ARSTRAT envelope limit at 2 degrees is -12.6dBW/Hz and, thus, this antenna off-axis ESD at 2 degree would be less than the ARSTART filing shown in Figure 2. The remainder of this paper will assess the systems impact of these transmit ESD levels.

**DISCUSSION**

In reference [7], a methodology and equations were developed to determine the SOTM ESD transmit impact to the ASN. It also utilized ITU-R S.738 to develop an ASN model. An ASN model is required to determine the impact of an off-axis ESD.

The assumption here will be that the ARSTRAT filed ESD envelope (-12.6 dBW/Hz @ 2 degrees) adhered to the single entry delta-T/T of 5% mandated by ITU-R S.738.

Determining the reference ASN is difficult at Ka-band, therefore, two WGS satellites will be used to perform the analysis. Reference [8], developed a model to determine the average WGS antenna gain. The key results of reference 8 are detailed below.

Within the main lobe of an axis-symmetric antenna, the gain $G(\theta)$ in a direction $\theta$ with respect to the boresight direction may be approximated by Equation 3.

$$G(\theta) = G - 12\left(\frac{\theta}{\alpha}\right)^2 \text{ dB} \quad \text{Eq}3$$

Where the expression is in decibels and the $G$ is the boresight gain and $\alpha$ is the 3dB beamwidth of the antenna.

To model the WGS spot beam and calculate the average EIRP and G/T value in a closed form we assume a uniform distribution of terminals inside that satellite beam. This first order approximation provides a useful solution for average EIRP and G/T within the beam. The average WGS beam values are obtained by mathematical integration of Equation 3 over the usable beamwidth which for WGS extends beyond the typical 3dB antenna beamwidth definition.

Using the calculated 3dB beamwidth $(1.19)^2$ but integrating over the usable beamwidth (1.71 degree) of a WGS the results shows that the average (typical) EIRP and G/T are only -1.7 dB below the beam center value. An additional reduction of 0.5dB was added to account for assumptions (simplification of the geometry) results in a total average reduction in gain of 2.2dB. Table 1 shows the average satellite parameters.

| BEAM | Average EIRP | Average G/T | Average Antenna Gain |
|------|--------------|-------------|----------------------|
| NCA  | 61dBW        | 11.5dB/k    | 40.2dBi              |

The Table 1 parameters were used for both victim and interfering networks\(^3\). In addition it was assumed that two adjacent satellite spot beams are aimed to the exact same spot on the earth with no angular antenna discrimination between victim and interfering network and no frequency discrimination.

\(^2\) Calculated value is a very close approximation to that of WGS design review data.

\(^3\) In the context of this paper the interfering network is the SOTM network and the victim network is the ASN.
Table 2 calculates the ESLNT and the delta-T/T for the case with the interfering ESD value of -12.6dBW/Hz at 2 degrees from boresight.

For this analysis, identical carriers are assumed for the networks on both the interfering and interfered with satellites. For the interfered with ASN, link budgets were prepared with four receive ET aperture sizes. Each of the link budgets were performed for a 20Mbps data-rate at an $E_b/N_0$ of 7.0dB with nominal uplink and downlink losses of 214.1 and 211.5dB respectively. Only Thermal Noise was considered in the link budget. The satellite transfer gain (STG), which is the electronic gain of the transponder plus the gain of the satellite antennas in the direction of the transmitting and receiving ET, was selected to provide exactly the required total link $C/N_0$. In Table 2, the resulting delta-T/T is 5%. The 5% value was chosen because above this value the ITU-R S.738 [4] requires coordination.

The equations used to solve for the delta-T/T are as follows. The link noise temperature was calculated using Equation 4

$$E_{LSNT} = \left( \frac{C}{N_0} \right)_{DN} \cdot T_{ET\_sum} \quad Eq\ 4$$

And the delta-T/T can be calculated using either Equation 5 or Equation 6. Equation 7 is used to calculate the transmission gain [4].

$$\Delta T = \frac{ESD \cdot \gamma \cdot G_{RX\_SAT\_ANT}}{T \cdot E_{LSNT\_Thermal} \cdot k \cdot l_g} \quad EQ\ 5$$

$$\Delta T = \frac{ESD \cdot \gamma \cdot T_{Satellite\_sum} \cdot \left( \frac{G}{T} \right)_{satellite}}{T \cdot E_{LSNT\_Thermal} \cdot k \cdot l_g} \quad EQ\ 6$$

$$\gamma = \left( \frac{C}{N_0} \right)_{DN} \cdot \frac{T_{ET\_sum}}{T_{Satellite\_sum}} \quad EQ\ 7$$

Where $T_{ET\_sum}$ and $T_{Satellite\_sum}$ are the system noise temperature (SNT) of the receive ET and the satellite respectively and $G_{RX\_SAT\_ANT}$ is the satellite receive beam antenna gain toward the interfering terminal.

For this analysis we assumed the interferers signal was towards the typical WGS G/T and, therefore, $G_{RX\_SAT\_ANT}$ was also the typical value.

Table 2 setup the ASN parameters with the current ARSTRAT ESD level of -12.6dBW/Hz. Table 3 below summarizes the impact of a single SOTM terminal when the transmit ESD level of a SOTM terminal is constrained to -19.2 dBW/Hz. The increase in the victim satellite SNT will require that the satellite EIRP is increased by 0.1dB

It should be noted that equations 5 and 6 will calculate the delta-T/T for the case when the bandwidth of the interfering carrier (BWI) is
equal to the bandwidth of the victim (BWV) carrier. In practice, however, MSS carrier bandwidth will be much smaller than the typical FSS carrier bandwidth.

Table 1’s delta-T/T of 1% is valid if the carrier bandwidths were equal (BWI = BWV) or if the sum of all of the SOTM narrow band carriers BWI approaches the BWV carrier.

When the BWI < BWV, the single entry interference impact is reduced by the ratio of the two carrier bandwidths $\frac{\Delta T}{T} = \frac{BWI}{BWV}$.

Figure 5 illustrates the case when BWI is less than BWV.

The impact of carrier bandwidths will be analyzed for two cases, a MSS narrow band carrier interfering with a FSS wide-band carrier (as illustrated in Figure 5) and a MSS narrow band carrier interfering with an adjacent MSS Narrow band carrier.

The single entry impact is calculated using equation 8.

$$\left( \frac{ESD \cdot \gamma \cdot G_{RX \_SAT \_ANT}}{ESLNT(THERMAL) \cdot k \cdot i_p} \right) \frac{BWI}{BWV}$$

eq8

The impact of a single entry SOTM carrier at (BWI) 768 kHz to the ASN carrier bandwidth of (BWV) 20 MHz is delta-T/T of 0.04%.

For the second case study with a MSS narrow band carrier interfering with another adjacent MSS Narrow band carrier the links will be based on the WIN-T POP terminal4.

This terminal has specified EIRP of 51.4dBW and a G/T of 14.4dB/K.

Since the ESD is related to EIRP by the following ratio $ESD_{max} = \frac{EIRP}{BW}$ the minimum bandwidth can be solved for given a maximum boresight ESD of -3.9dBW/Hz. The result is 339 kHz; therefore, both MSS links will be set to 384kbps5. Table 4 shows the delta-T/T at 8.8%. This increase over the previous cases is due to the required higher satellite electronic gain needed to compensate for both the lower transmit EIRP and the receive G/T of the SOTM terminals.

WIN-T SOTM NETWORK IMPACT

A WIN-T Brigade Combat Team (BCT) deployment can consists of up to 65 SOTM terminals with an estimated transmit duty cycle of 10% to 30% for each SOTM terminal. Multiple BCT deployments are possible to a given region serviced by a single WGS spot beam.

Table 4 Impact MSS to MSS

| ARSTRAT ESD Value at 2 Degree (dBW/Hz) | Link C/N0up (dB-Hz) | Link C/N0dn (dB-Hz) | Link C/N0total (dB-Hz) | Satellite (G/T) sat (dB/K) | Satellite SNT (K) | Satellite Gain (dBi) | Rx ET diameter (m) | Rx ET antenna gain (dB/K) | Rx ET antenna ET SNT (K) | Rx ET antenna ESLNT (K) | T of the ESD (K) | $\Delta T \over T$ | New ESLNT (K) | Increase Satellite EIRP (dB) |
|--------------------------------------|---------------------|---------------------|------------------------|----------------------------|-------------------|---------------------|---------------------|------------------------|-----------------------|----------------------|-----------------|---------------|-----------------|---------------------|
| -19.2                                | 77.4                | 60.5                | 60.4                   | 11.5                      | 741.3              | 40.2                | 191.7               | 0.6                    | 14.4                  | 39.96                | 360.0           | 367.4         | 35.4            | 8.8%               | 402.8              | 0.4            |

4 WIN-T Mobile Point of Presence
5 384kpbs is the nearest Network Centric Waveform (NCW) implemented data-rate with an Eb/N0 of 4.6dB
This paper has shown that the worst case occurs when ASN are both configured for MSS services. Adjacent MSS networks would result in an overall delta-T/T of 8.8%. In this case, both of the ASN(s) would require an increase in satellite EIRP of 0.4dB to overcome the increase in the apparent equivalent SNT. However, as shown in Table 4, the link C/N0total equals 60.4dB-Hz with an adjacent ESD level at -19.2dBW/Hz. The corresponding C/I_esd would equal 70.6dB-Hz reducing the link C/N0total to 60.0dB-Hz. Increasing the on-axis EIRP by 0.4 dB will also increase adjacent ESD by 0.4dB to a level of -18.8dBW/Hz, but the C/I_esd remains at 70.6dB-Hz. The link total returns to C/N0total 60.4dB-Hz; the resulting delta-T/T, however, would be raised to 9.6% which is less than a 1% increase.

However, because this is a severe case study, and since SOTM services will always have some finite transmit duty-cycle, the impact is not as significant. Even when networks are not strictly MSS, the delta-T/T of 8.8% is slightly higher than the recommendation of ITU-R S.738. Conversely, if the ESD limit was set to the commercial Ku-band value at 2 degrees of -28.5dBW/Hz the bandwidth would have to be expanded by almost a factor of x10!

The very low return in saved satellite EIRP does not warrant the almost x10 increase in satellite bandwidth.

Given that the World Radio Regulations has designated the earth-to-space 30-31 GHz Ka-band, a usage designation of co-primary fixed satellite (FSS) and mobile satellite service (MSS), this level seems to strike the correct balance between MSS and FSS requirements. The current ARSTRAT ESD limit is appropriate for the new MSS Service.

CONCLUSION

The conclusion is that the current ARSTRAT off-axis ESD envelope is appropriate for SOTM operations. The maximum ESD for a particular SOTM antenna will be determined by its antenna pattern and antenna pointing accuracy. In the example used in this paper, the 1% delta-T/T (for the single entry SOTM transmitter) is well below the ITU-R S.738 limit for FSS services.

The World Radio Regulations has designated the earth-to-space 30-31 GHz Ka-band with a usage designation of co-primary fixed satellite (FSS) and mobile satellite service (MSS), therefore, it is appropriate that compromises with mutual interference levels are made. The fact that SOTM requires narrow spot beams leads itself nicely to frequency, polarization, and antenna discrimination by interleaving spot beams over the geographic region of interest which can further reduce the interference impact. Given all of the above, the proposed performance requirements for the new class of Ka-band SOTM will provide enough safeguard performance to strike the correct balance of quasi interference-free operations, while maintaining reasonable spectral efficiency.

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