Restrictions Imposed for Simultaneous High Data Rate Telemetry and Varying Modulation Index Commanding[1,2]

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Abstract—Specifications for the Air Force Satellite Control Network (AFSCN) identify limitations for the total modulation index and telemetry data rates permitted. This paper investigates the limitations on Space-Ground Link Subsystem (SGLS) telemetry and commanding performance due to varying combinations of command modulation index and telemetry data rates. The downlink SGLS signal investigated in this paper includes the telemetry data and the commanding echo data. Ranging data is not included since the ranging modulation index is small and does not interfere with the telemetry data to any significant degree. Analysis of the downlink signal will be presented to show the limitations of the command modulation index and the telemetry data rate. Current specifications for the Satellite Space/Ground Interface allow a telemetry data rate of 256 kilobits per sec (kbps) for any combination of downlink ranging, commanding, and telemetry modulation indices given the total modulation index is less than or equal to 3.0 radians (rad). It was found that the total modulation index is much more restrictive than the 3.0 rad specification and is dependent on the telemetry data rate.

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1. INTRODUCTION

Satellite design engineers must ensure that their systems adhere to the system and interface specification documents to guarantee desired system performance. Of course, this is under the caveat that these documents contain correct information. In at least one instance, the author has found that the specifications are not correct. This places the burden on the design engineers to ensure that their designs will work with the actual system as they anticipated.

This paper addresses a problem with the parameters for a new satellite. According to the specifications, the AFSCN system should be able to accommodate an uplink or downlink signal consisting of commanding, ranging, and telemetry. The system should work for any combination as long as the total modulation index for this signal is less than 3.0 rad. The new satellite required modulation indices of 1.0, 1.3, and 0.3 rad for commanding, telemetry (256 kpbs on a 1.7 Megahertz [MHz] subcarrier) and ranging, respectively. Since these requirements fall within the specification, the system should have worked as planned. However, the system did not work as designed. As will be shown later, the problem was caused by a high data rate telemetry signal used in combination with a higher than usual command modulation index.

The AFSCN is tasked with maintaining command and control of satellites under its responsibility so users can be assured continued access to data for their programs. Commanding, ranging, and downlink of telemetry data are the three crucial functions required of the AFSCN. These three functions are accomplished by combining commands and a ranging signal into a baseband signal that phase modulates the uplink carrier. In the satellite, commands are recovered along with the ranging signal. This information is combined with the telemetry data to modulate the downlink carrier.

The baseband signal used in the SGLS downlink signal consists of ranging, commanding, and telemetry signals. The theoretical baseband spectrum is shown in Figure 1. Only relative amplitudes for the three components are shown.

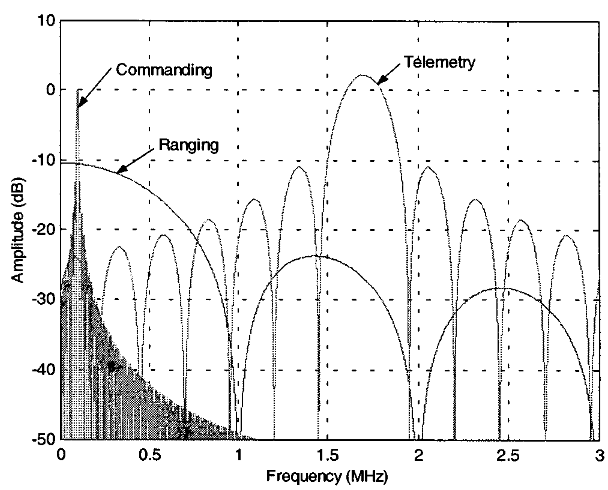

Figure 1. Theoretical SGLS Baseband Spectrum.

Ranging is a pseudorandom (PRN) code signal consisting of pulses at a 1 MHz rate. Ternary commands are used to form

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[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

[2] Updated December 16, 1999

a frequency shift keyed (FSK) signal. The command signal is a 1, 2, or 10 kbps signal and is created by amplitude modulating the FSK signal with a triangle wave at half the command rate. The triangle envelope is recovered at the receiver and is used for timing. Telemetry data binary phase shift key (BPSK) modulates the subcarrier to generate the telemetry signal. Telemetry data rates are typically 32 kbps, 64 kbps, 128 kbps, or 256 kbps. Three different downlink subcarriers are used: 1.024 MHz, 1.25 MHz, and 1.7 MHz. Only low data rate telemetry use the lower frequency subcarriers. Telemetry at the 256 kbps rate always uses the 1.7 MHz subcarrier. Commanding, telemetry and ranging are summed and the composite baseband signal phase modulates the Radio Frequency (RF) carrier. Specifications for the total modulation index [1,2] allow a maximum of 3.0 rad for the downlink SGLS signal regardless of the data rate.

Ranging modulation indices are usually either 0.125 rad or 0.3 rad. Because of the low modulation index and the nature of the PRN spectrum, the ranging energy is spread out and does not cause any significant interference with the telemetry information modulated on the subcarrier. Interference to the telemetry caused by the command signal had not previously been an issue because only low command modulation indices had been used with the 256 kbps telemetry signal. Parameters introduced for a new series of satellites are now requiring a higher modulation index for the command signal and a data rate of 256 kbps for the telemetry signal. Despite having a total modulation index of less than 3.0 rad for the composite SGLS signal, operational testing showed that the telemetry information could not be recovered for this combination of telemetry data rate and command modulation index.

This paper presents an analysis of the fundamental signals and modulation that shows the intermodulation products from the command and telemetry signals are the cause of the interference preventing the recovery of the telemetry data. Experimental results conducted in the Automated Remote Tracking Station (ARTS) Development and Modification Facility (ADMF) are presented that verify the analysis.

This paper is organized into four sections: Section I gives a basic background on the SGLS signal used in the AFSCN. Section II presents the theoretical analysis of the effects of phase modulating a carrier with a baseband signal consisting of a linear sum of the commanding, telemetry, and ranging signals. Experimental results of testing in the ADMF are presented in Section III. Finally, Section IV presents conclusions and recommendations.

2. Mathematical Analysis

Phase modulation of a carrier produces a potentially complicated sideband structure. However, if the modulating signal is a sine wave, the amplitude of the sidebands are determined by first order Bessel functions. When multiple signals phase modulate a carrier, the sideband structure is more complex. Each component of the composite modulating signal modulates the carrier and creates sidebands dependent on the Bessel functions. However, intermodulation products are also created by the interaction of the components of the composite baseband signal.

A mathematical analysis of the interaction between the components of the composite baseband signal shows the degree of interference to the various components likely during the demodulation process. Both the satellite downlink signal and the ADMF test signal consist of a carrier phase, modulated by a composite baseband signal consisting of the commanding, telemetry, and ranging information. Similar to an analysis in [3], the transmitted signal is mathematically represented as:

$$s(t)=\sqrt{2P_T}\sin\left(\omega_c t+\left(\begin{matrix}\beta_{CMD}x_1(t)+\\ \beta_{TLM}x_2(t)+\\ \beta_{RNG}x_3(t)\end{matrix}\right)\right) \quad (1)$$

where ω_c is the carrier frequency and β_{CMD}, β_{TLM}, and β_{RNG} are the modulation indices of the commanding, telemetry, and ranging signals, respectively. The modulation indices used in this study for commanding, telemetry, and ranging were 1.0, 1.3, and 0.3 rad, respectively. The commanding, ranging, and telemetry signals, $x_1(t)$, $x_2(t)$, and $x_3(t)$ are defined as:

$$x_1(t)=\left(1+km(t)\right)\cdot\sum_{n=-\infty}^{\infty}\sin\left(2\pi f_1^{(n)}t\right)\cdot P(t-nT_1) \quad (2)$$

where $f_1 \in$ {65 kHz, 76 kHz, or 95 kHz}, $P(t)$ denotes square pulses, $m(t)$ denotes the triangular amplitude modulating waveform, and k is the amplitude modulation factor (normally equal to 0.5):

$$x_2(t)=d(t)\sin(2\pi f_2 t) \quad (3)$$

where $d(t)$ equals ±1, and f_2 is the subcarrier frequency:

$$x_3(t)=d_r(t)\equiv\sum_{k=-\infty}^{\infty}d_r^{(k)}\cdot P_3(t-kT_3) \quad (4)$$

where $d_r(t)$ equals ±1 and $P_3(t)$ denotes square ranging pulses.

For the case of this analysis, only the interaction between the commanding signal and the telemetry signal is of interest. Thus, (1) can be simplified by ignoring the ranging signal. Additional simplification is achieved by assuming the commanding signal is not amplitude modulated and that only one tone is used. For the mathematical analysis, a final simplification is achieved by not BPSK modulating the subcarrier. After applying these simplifications, (1) can be simplified to:

$$s(t)=\sqrt{2P_T}\sin\left(\omega_c t+\left(\begin{matrix}\beta_{CMD}\sin(\omega_1(t))+\\ \beta_{TLM}\sin(\omega_2(t))\end{matrix}\right)\right) \quad (5)$$

After expansion of (5) using trigonometric identities and simplification [4], the result shown in (6) is obtained.

$$
s(t)=\sqrt{2P_T}\cdot\left\{\begin{array}{l}
J_0(\beta_1)\cdot J_0(\beta_2)\cdot\sin(\omega_c t)\\
-2J_0(\beta_2)\begin{bmatrix}J_1(\beta_1)\cdot\cos(\omega_1 t)\cos(\omega_c t)\\ -J_2(\beta_1)\cdot\sin(2\omega_1 t)\sin(\omega_c t)\end{bmatrix}\\
-2J_0(\beta_1)\begin{bmatrix}J_1(\beta_2)\cdot\cos(\omega_2 t)\cos(\omega_c t)\\ -J_2(\beta_2)\cdot\sin(2\omega_2 t)\sin(\omega_c t)\end{bmatrix}\\
-4J_1(\beta_2)\begin{bmatrix}J_1(\beta_1)\cdot\cos(\omega_1 t)\sin(\omega_c t)\\ +J_2(\beta_1)\cdot\cos(2\omega_1 t)\cos(\omega_c t)\end{bmatrix}\cdot\cos(\omega_2 t)\\
-4J_2(\beta_2)\begin{bmatrix}J_1(\beta_1)\cdot\cos(\omega_1 t)\cos(\omega_c t)\\ -J_2(\beta_1)\cdot\cos(2\omega_1 t)\sin(\omega_c t)\end{bmatrix}\cdot\cos(2\omega_2 t)
\end{array}\right\} \quad (6)
$$

In (6), $J_n(x)$ denotes a Bessel function of the first kind of order n and argument x (or modulation index in this case). Only the Bessel function components for $n<3$ are included in (6) because the remaining components for $n\geq 3$ are either too small or are filtered out in the receiver demodulation process. Equation (6) shows that when a carrier is phase-modulated by a baseband signal consisting of a linear combination of signals, each component phase modulates the carrier and produces sidebands according to its modulation index and the Bessel functions associated with that index. The first term in (6) is the carrier component of the phase-modulated signal. Terms two and three are the carrier phase modulated by the command signal and the telemetry subcarrier, respectively. These terms give rise to frequency components at $\omega_c \pm n\omega_1$ and $\omega_c \pm n\omega_2$, respectively. The last two terms give rise to the intermodulation products between the commanding and telemetry subcarrier.

The severity of the interference caused by the commanding and telemetry subcarrier intermodulation product is dependent on the modulation index of the command signal component and the data rate of the telemetry signal. A plot of the relative levels of the sidebands caused by the intermodulation term is shown in Figure 2.

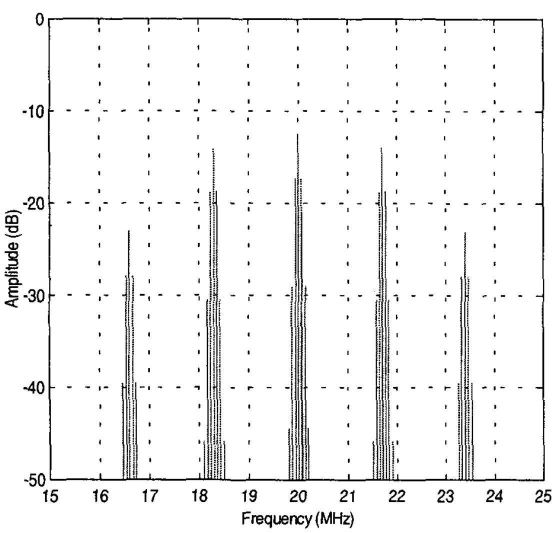

Figure 2. Theoretical SGLS Spectrum

For this plot, a 1.7-MHz subcarrier is used for the telemetry signal, which has not been BPSK-modulated with data. The command and telemetry modulation indices are 1.0 and 1.3 rad, respectively. The command signal is a 65 kHz sine wave. A carrier frequency of 20 MHz is used to increase the speed of the calculation. This does not change the amplitudes of the sidebands or the locations relative to the carrier frequency.

Figure 3 shows the relative levels of the spectrum when data BPSK modulates the telemetry subcarrier. The data rate is 256 kbps. Even though the intermodulation products are not visible in the subcarrier lobe, they are present. Because most of the telemetry signal energy is contained in the main subcarrier lobe, demodulation normally uses only the energy contained in that main subcarrier lobe. Filtering captures the main lobe while eliminating the rest of the spectrum as noise. This method maximizes the signal to noise ratio (SNR). However, because the intermodulation products are positioned in the subcarrier lobe, they cannot be removed without removing a substantial portion of the telemetry signal energy. Thus, no filtering to remove the command intermodulation products is possible.

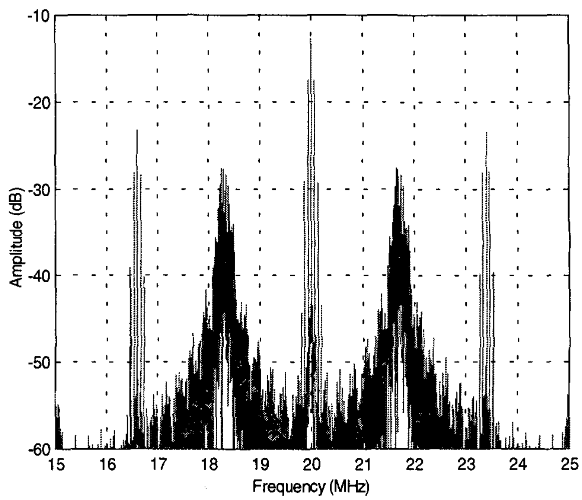

Figure 3. Spectrum with Commanding and Telemetry Data

Two possible methods of minimizing or eliminating this interference are indicated by (6). First, by decreasing the command modulation index, the amplitude of the intermodulation products can be decreased sufficiently to minimize interference in the demodulated telemetry signal. Increasing the command tone frequency provides a second method to eliminate the interference. The main subcarrier lobe is 512 kHz wide for telemetry data at a 256 kbps rate. Since the bandwidth of the receiver should be minimized to decrease the received noise level, if the command tones are increased to a frequency greater than 256 kHz, the intermodulation products will occur outside the main subcarrier lobe. This will effectively eliminate the interference with the telemetry signal. Both of these methods were verified with actual testing in the ADMF.

3. Experimental Results

To test the hypothesis that the intermodulation product between the commanding and telemetry subcarrier signals causes the interference in the demodulated telemetry information, four experiments were conducted in the ADMF. The command modulation index was decreased in the first experiment. In the second experiment, the command frequency was increased using the built in equipment. An external signal generator was used in the third test so a continuous variation in the command tone frequency could be done. Finally, the telemetry data rate was decreased in the fourth experiment. Figure 4 shows the signal flow through the equipment in the ADMF.

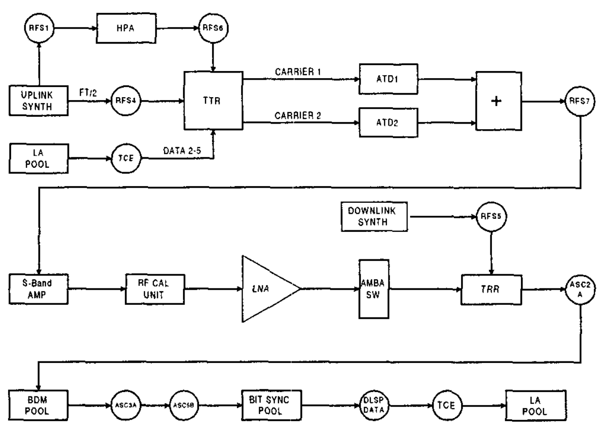

Figure 4. Signal Flow in the ADMF.

The uplink carrier is phase modulated by the command and ranging signals. After amplification by the HPA, the test transponder (TTR) receives the signal and recovers the ranging and commanding information. Telemetry data from the link analyzer (LA) then BPSK modulates the subcarrier in the TTR. The telemetry subcarrier, commanding, and ranging signals are then combined for phase modulation of the downlink carrier. Signal flow after the TTR is typical. The signal goes through an LNA, the receiver (TRR), a BPSK demodulator, bit synchronizer, and finally the data goes back to the link analyzer for bit comparison to calculate the Bit Error Rate (BER).

After configuring the system to generate command tones and telemetry for the baseband signal, a telemetry BER loop was set up. Because of the test transponder limitiations, the initial configuration set the modulation indices to 1.0 rad and 1.2 rad for commanding and telemetry, respectively. Since the interference is caused by the high command modulation index and is independent of the telemetry modulation index, this difference does not change the results. The telemetry data rate was 256 kbps. With these parameters, the link analyzer failed to lock to the received data.

The command modulation index was then decreased until link analyzer lock was achieved and no errors were recorded. Lock was achieved and no errors were detected when the command modulation index was reduced to 0.6 rad. This test verified that interference to the telemetry signal could be eliminated if the command modulation index was reduced sufficiently.

The second method suggested in Section II to eliminate the interference was to change the command tone frequency. Increasing the command tone frequency moves the intermodulation products further away from the subcarrier frequency. If the command tones are greater than 256 kHz, the intermodulation products will occur outside the main subcarrier lobe. Two methods were used to change the command tone frequency.

Standard SGLS equipment allows either low or high frequency command tones. The standard low frequency tones are 65, 76, and 95 kHz, and the high frequency tones are 0.975, 1.025, and 1.075 MHz for 1, 0, and S-tones, respectively. If the high frequency tones are used, the intermodulation products occur outside the main subcarrier lobe containing telemetry information. After changing the system to use the high frequency tones, the BER test was repeated. Lock was immediately obtained and no errors were detected regardless of the command modulation index.

For the third test, an external, variable frequency, sinusoidal generator was used as the command tone source. Initial failure was verified by setting the generator to provide a 0.5-V_{pp}, 65 kHz sine wave. This signal was combined with the telemetry subcarrier for subsequent modulation of the carrier. With the signal generator set to 65 kHz, the test failed as expected. The frequency of the signal generator was then varied from 65 kHz to 300 kHz. As the frequency of the simulated command tone was increased, the number of bit errors decreased. After the frequency was increased to greater than 256 kHz, there were no more detectable bit errors.

In the last test, the telemetry data rate was decreased. Decreasing the data rate changes the width of the main lobe in relation to the command tone frequency, effectively moving the intermodulation products outside of the main subcarrier lobe. When the data rate was decreased below 64 kbps, the intermodulation products occurred outside the main subcarrier lobe and no errors were detected.

These tests verify that if the intermodulation products of the command signal with the telemetry subcarrier are moved outside the main subcarrier lobe, the interference is eliminated and the telemetry data can be recovered with the expected system BER.

With the exception of a tracking antenna, the ADMF has all the equipment of a fully functioning ground station. The results obtained with the ADMF are indicative of actual performance obtained with the equipment at operational ground stations. Thus, the hypotheses formed from the mathematical analysis in Section II were confirmed by the experimental results obtained in the ADMF.

4. CONCLUSION

Engineers must use interface specifications to design satellites such that communication and transfer of data will be guaranteed. At least one error has been found in the ARTS and space to ground interface specifications. The error is an incorrect value for the total modulation index allowed for the SGLS signal. This condition was identified when a satellite with more demanding parameters was introduced into the AFSCN. Even though the parameters specified in the setup configuration were not exceeding the system specifications, testing revealed that telemetry could not be received. Further analysis and testing verified telemetry reception is impossible using the parameters specified. Users and satellite designers need to be aware that high command modulation indices are not possible when using high data rate telemetry. Perhaps there may possibly be other errors in the specifications that will come to light when new satellites with even more demanding requirements are built.

REFER

[1] System Specification for the ARTS, SS-ARTS-001B, May 17, 1993.

[2] Standardized Interface Specification between AFSCN Common User Element and Comm/Range Segment and Space Vehicle, AFSCN SIS-000502, September 9, 1999.

[3] Tien M. Nguyen, Charles C. Wang, Andrew S. Parker, James Yoh and John M. Charroux, "Impact of Baseband Filtering on the SGLS Waveform," *1999 IEEE Aerospace Applications Conference Proceedings*, March 1999.

[4] William C. Lindsey and Marvin K. Simon, *Telecommunication Systems Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, 1973.

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