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High-Data-Rate Quadrax Cable Microwave Characterization at the NASA Glenn Structural Dynamics Laboratory

Onoufrios Theofylaktos, Joseph D. Warner, and Charles J. Sheehe
Glenn Research Center, Cleveland, Ohio

October 2012

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Summary

An experiment was performed to determine the degradation in the bit-error-rate (BER) in the high-data-rate cables chosen for the Orion Service Module due to extreme launch conditions of vibrations with a magnitude of 60g.

The cable type chosen for the Orion Service Module was #8 quadrax cable.

The increase in electrical noise induced on these #8 quadrax cables was measured at the NASA Glenn vibration facility in the Structural Dynamics Laboratory. The intensity of the vibrations was set at 32g, which was the maximum available level at the facility. The cable lengths used during measurements were 1, 4, and 8 m.

The noise measurements were done in an analog fashion using a performance network analyzer (PNA) by recording the standard deviation of the transmission scattering parameter S_{21} over the frequency range of 100 to 900 MHz. The standard deviation of S_{21} was measured before, during, and after the vibration of the cables at the vibration facility. We observed an increase in noise by a factor of 2 to 6. From these measurements we estimated the increase expected in the BER for a cable length of 25 m and concluded that these findings are large enough that the noise increase due to vibration must be taken in to account for the design of the communication system for a BER of 10^{-8}.

Introduction

Quadrax cables have been selected to be used on the Orion Service Module (SM). The maximum path length the service module may need to span is approximately 25 m. The Orion Team has proposed to use 802.3 Clause 39 as a recommended standard for the quadrax cable properties (Ref. 1). The cables are to carry low-voltage differential signals (LDVS). Because of the length of the cable and the voltage drop across them, there is concern that noise due to vibration of the cable introduced during the launch of the Orion SM might increase the bit error rate (BER) at the detector to be greater than 10^{-8}.

To determine the expected increase in the BER the standard deviation s_{21} of the transmission scattering parameter (transmission coefficient) S_{21} was measured before, during, and after vibration at 32g using a performance network analyzer (PNA). The increase in s_{21} during vibration can be related to the expected increase in the BER of the communication system. The method of relating s_{21} to BER is shown later in this report.

The measurement of s_{21} was performed over the frequency range of 100 to 900 MHz. This frequency range covers the fundamental frequency of 625 Mbps when using the proposed 5-bit word length.

The communication system is designed to send 625 Mbps down each wire pair in the #8 quadrax cable. The level of the signal traveling down one of the quadrax pairs must exceed the minimum voltage detection by at least 5.61 standard deviations of the noise voltage as determined by the measurements of S_{21}.

Cable and Balun Description

Several quadrax cables of different length are planned to be used in the Orion SM and elsewhere. These cables are manufactured by W.L. Gore. An Agilent PNA was used to analyze 1-, 4-, and 8-m quadrax cables to obtain the full set of *S*-parameters.

The model of the Gore quadrax cables that were measured was ACN1037, and the part numbers for the 8-m cables are DDA0187-SPSA-0800_1 and DDA0187-SPSA-0800_2, for the 4-m cable is DDA0187-SPSA-0400_1, and for the 1-m cable is DDA0187-SPSA-010_1. Inside these quadrax cables there are two pair of 150-W, 24 American Wire Gauge (AWG) wires. These two pairs are arranged so that the two planes that each pair forms are orthogonal to each other. The cross section of the wire geometry does not vary down the length of the cable (Ref. 2).

To be able to measure the transmission loss and the noise on each of the cable with the PNA, we used a 150- to 50-W balance-to-unbalance transformer (balun). This arrangement necessitated the use of "pigtails" (Ref. 2) from Gore to mate the quadrax cables to the baluns. The pigtails were constructed as follows: one end of each of the pigtail cables was four wires without the sheath and on the other end was either a male or female quadrax connector. These 0.61-m cables part numbers are DDA0187-SPSA-0061_J1 with the male #8 quadrax connector and a pigtail 3214735-02_PIGTAIL, and DDA0187-SPSA-0061_J2 with a female #8 quadrax connector and a pigtail 3214735-02_PIGTAIL.

The baluns used were procured from Pulse Engineering under part number HFB050150. The turns ratio of these transformers was 3. The specification of the baluns gave a maximum operating frequency of 1200 MHz, although in this experiment the maximum frequency was limited to only 900 MHz because of anomalies in the baluns' performance above 900 MHz. Each transformer had a 50-W SMA connector at the one port (primary) and three 838-µm (inner diameter) DB-type sockets at the 150-W port (secondary). The middle socket on the 150-W side (secondary) was internally connected to the primary ground.

The *S*-parameter measurements on the cables were done with the PNA connected to the 50-W port of the baluns and the pigtails connected to the 150-W port of the baluns. The cables that were measured were connected between the quadrax connectors of the pigtail cables.

Experimental Approach

To make the noise measurements of the cables, first the baluns had to be characterized and then calibrated out of the measurement on the cable. After that was done, the cable *S*-parameters were measured before the vibration run of the cable, during the time the cable was being vibrated at the maximum acceleration, and then after the vibration run.

The radiofrequency (RF) measurements (*S*-parameters) were done using a PNA (M/N: N5230A, S/N: MY46400910). The PNA's most recent calibration was performed in December of 2010 (Agilent Cal 1-2869640062-1). The cable lengths measured were 1, 4, 8, and 16 m long. Two 8-m daisy-chained cables were used for the 16-m measurement with a bulkhead connector (Fig. 1), and without a bulkhead connector (Fig. 2). Comparing the measured noise and losses in the 16-m cable with and without the bulkhead fitting characterizes the bulkhead fitting for launch applications.

The cable *S*-parameters were measured between 100 to 900 MHz using 6401 points. Each cable set was measured before, during, and after vibration, 36 times in each case. The individual sets of scans taken before, during, and after vibration of the cables were averaged to calculate the standard deviation of the *S*-parameters at each frequency point. There was no weighting factor used in determining the average value or the standard deviation of the *S*-parameters. The S_{21} parameters between sets were compared to determine the increase in the noise due to vibration of the cables.

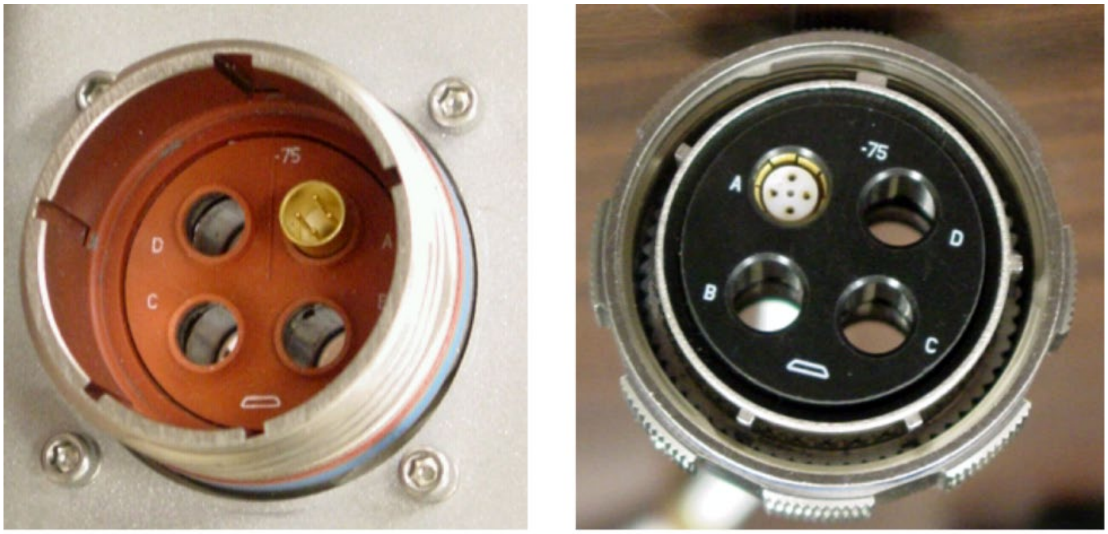

Figure 1.—Bulkhead connectors with #8 quadrax connectors (male/female) shown in slot A.

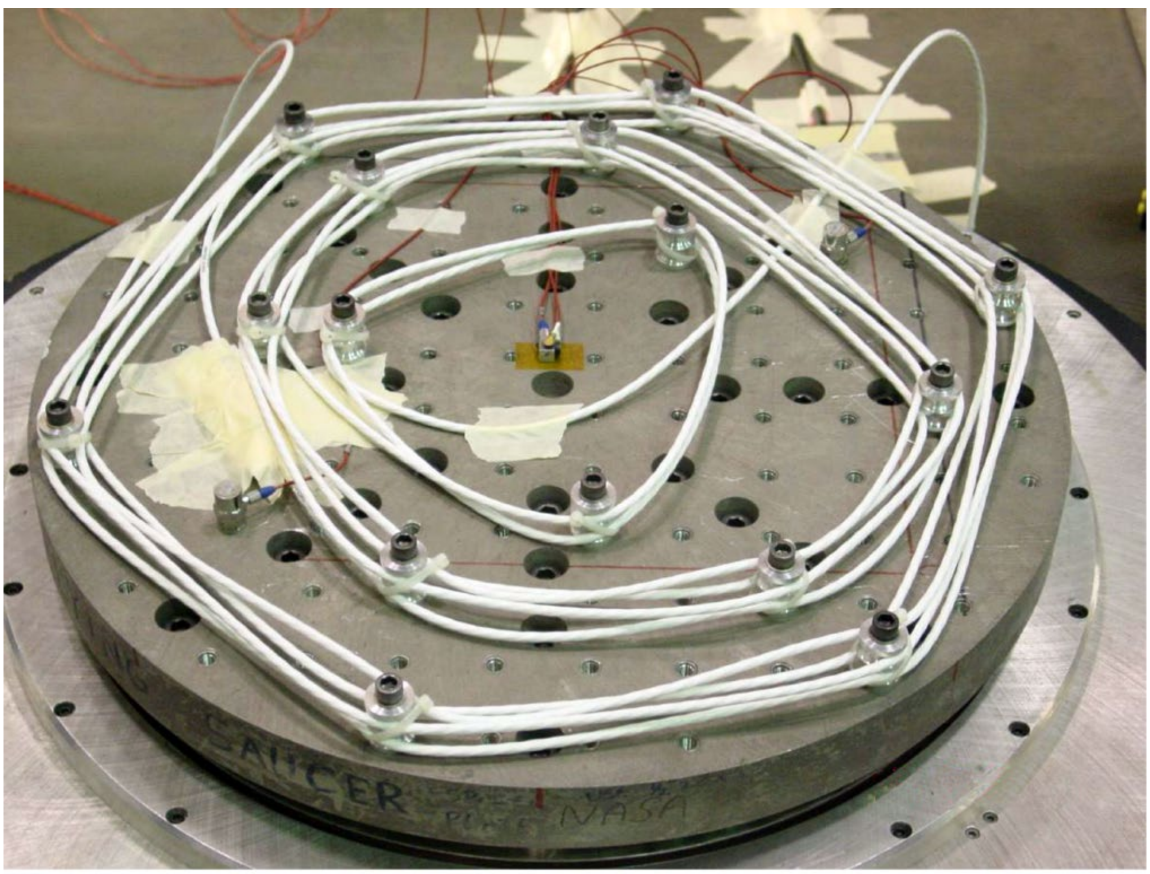

Figure 2.—Two 8-m quadrax cables coupled together without bulkhead connector.

Between 100 and 900 MHz the extinction and reflection coefficients were measured versus frequency for the different lengths of cable. The extinction and reflection coefficients were extrapolated to 1250 MHz after which the insertion loss at 1250 MHz and cable length of 25 m was calculated. Note 1250 MHz is twice the fundamental highest digital rate of 625 Mbps, and 25 m was the estimated longest cable run on Orion.

Characterization of Balun Ensemble at 50 W Using the PNA

To calibrate the baluns and the cable measurements, in-house calibration kits were fabricated as there were no 150-W certified quadrax calibration kits available. The calibration kits were made—one for each gender with open quadrax connectors, shorted quadrax connectors, and load quadrax connectors. The shorted connectors connected the two wires in each pair of the quadrax connectors together making sure the two pair of wires did not touch one another. The open connectors left the wires open inside of the quadrax connector. The load connectors were made by placing a 150-W, 0.1 percent accurate non-inductive resistor across each pair of wires. The through measurements connected the two ends of the quadrax cables together. Figure 3 shows the schematic of the calibration of the 150-W baluns.

Calibration procedure for the baluns:

(1) Specify Frequency range from 100 to 2000 MHz.
(2) Calibrate out PNA cables with 50 Ω connector terminations.
(3) Place balun circuits between PNA cables (Fig. 3).
(4) Measure 2-Port *S*-parameters of balun ensemble using the PNA.
(5) Disassemble/assemble and verify repeatability of measurement.
(6) Document results.
(7) Calibrate out PNA cables with balun ensemble (Fig. 4). Each balun box should be terminated using the 150-Ω test kit as shown in Figure 5 prior to testing of any cables.

The calibration results of the baluns are given in Reference 2.

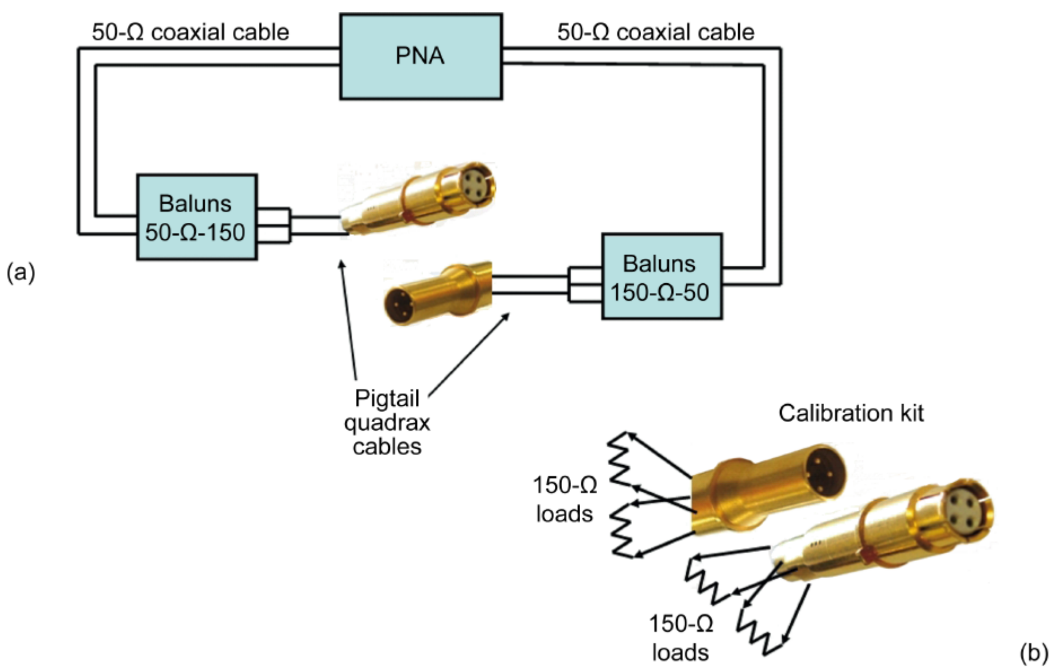

Figure 3.—Calibration of performance network analyzer (PNA) with baluns. (a) Measuring equipment with balun pair and pigtail cables included. (b) Illustration of how 150-Ω test load was made.

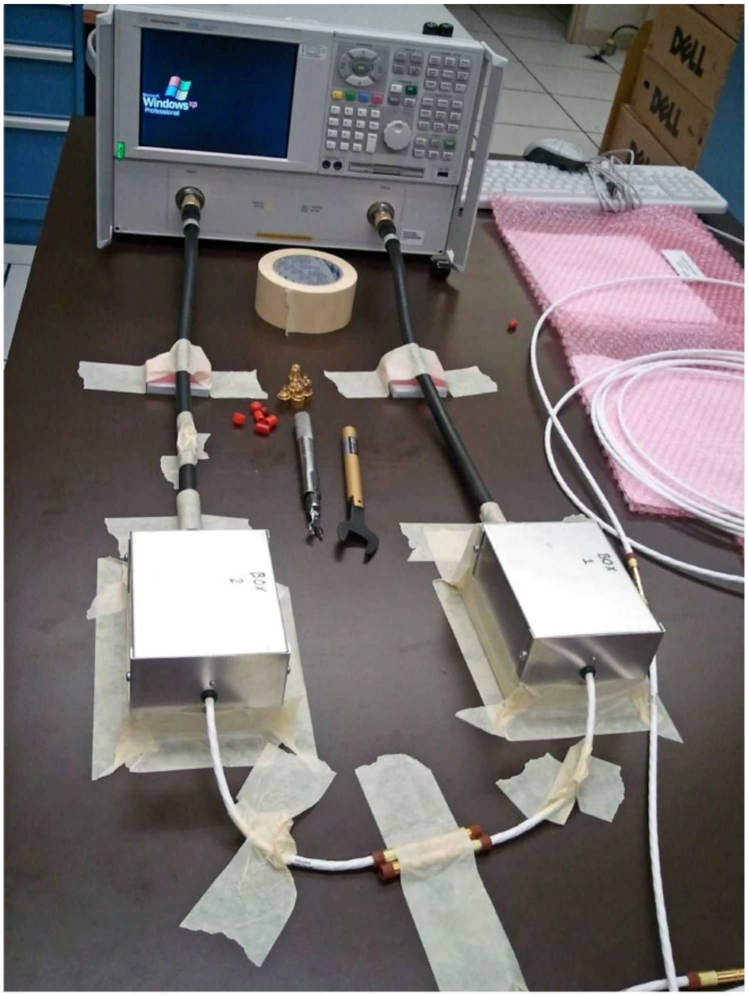

Figure 4.—Typical calibration of performance network analyzer (PNA) with baluns and pigtail cables terminated with the calibration kit.

Figure 5.—Load, short, and open terminators for the 150-Ω performance network analyzer (PNA) calibration kit.

Characterization of Quadrax Cable

The characterization procedure of the quadrax cable under static and dynamic conditions for the measurements before, during, and after vibration is listed below:

(1) Set frequency range between 100 and 900 MHz.
(2) Place cable of the device under test (DUT) between the two balun boxes.
(3) Measure 2-port *S*-parameters of each DUT using the PNA.
(4) Repeat (3) and save a total of 36 files.
(5) Repeat (2) for different lengths of cable (24 AWG only).
(6) Document results.

Data Analysis

The PNA gives the *S*-parameters in decibels. Prior to averaging the *S*-parameters, they were all converted from decibels to a simple ratio of powers from the magnitude of the *S*-parameters. After this conversion was done the average and the standard deviations were computed for all the *S*-parameter from the 36 sweeps of the frequency range.

Only the S_{21}-parameters were used for subsequent analyses to determine the effect of vibration on the noise in the system because only the properties of S_{21} affect the bit error rate of the system (Ref. 3). From the measurement of S_{21} one can relate the magnitude and the noise to the energy in one bit (E_b) to the average energy of the noise ($N0$) within one bit time period (T_b). The relationship of $E_b/N0$ to the magnitude of S_{21} and its standard deviation σ_{21} is given by Equation (1) (Ref. 3):

$$\frac{E_b}{N0} = \frac{S_{21}}{\sigma_{21}} \tag{1}$$

where

$$E_b = \frac{V^2}{R} T_b \tag{2}$$

V is the voltage of the bit pulse, and R is the impedance of the circuit or the resistance over which the signal is measured.

Equation (1) assumes that the noise is additive white gaussian noise across the bandwidth of the system to be able to calculate $N0$.

The $E_b/N0$ can be turned into a ratio of the reference voltage divided by the standard deviation simply by taking its square root. This is true for uncorrelated bits. So for uncorrelated bits the relationship is

$$\frac{V}{\sigma_v} = \sqrt{\frac{E_b}{N0}} \tag{3}$$

where V/σ_v is the number of standard deviations of the voltage noise that the system can handle before a bit is incorrectly detected; note $V/\sigma_v = \sqrt{2E_b/N0}$ for bi-polar shift keying (BPSK) (Ref. 3). For correlated signals one must multiply E_b by the number of bits that are correlated together. For correlated BPSK modulation this factor is 2.

Since calculations of BER curves use the Q function, it is easy to relate measured analog noise in the system to the system BER.

The Q function is defined as

$$Q(x) \equiv \frac{1}{2}\left[1 - \operatorname{erf}\left(\frac{x}{\sqrt{2}}\right)\right] \tag{4}$$

where x is the number of standard deviations and erf is the error function; therefore $x = V/\sigma_v$.

Cable Losses

The losses in the cables are plotted below. Figure 6 gives the cable loss in the 8-m cable-1 (8M1). Figure 7 gives the cable loss in the 8-m cable-2 (8M2). Figure 8 gives the cable loss in the 16-m cable without a bulkhead connection (16MNB). Figure 9 gives the cable loss in the Gore 16-m cable with a bulkhead connection (16MBH). The cable loss is given in Equation (5). It is 1 minus the reflection coefficient minus the transmission coefficient:

$$\text{Cable loss} = 1 - S_{11} - S_{21} \tag{5}$$

In each of the figures the losses before, during, and after the vibration are plotted. As one can see, the losses are gradually increasing with frequency. The high frequency peaks in the plots come from the standing waves in the cable. Furthermore, the cable loss due to vibration is higher than the cable loss before and after vibration.

In all four cable measurements the losses increase monotonically with frequency except in the region of 600 to 700 MHz. From the size of the standing wave in that region, the impedance is not as well matched as at other frequencies, but always the losses measured during vibration is greater than before or after vibrating. As one can see between cable 8M1 and 8M2, which are of the same length, 8 m, there is virtually no difference in the cable losses as seen in Figures 6 and 7.

The standard deviation in the cable losses from Figures 6 to 9 is plotted in Figures 10 to 13 and is determined from the propagation of errors using the uncertainties of S_{11} and S_{21} by utilizing the following equation:

$$\sigma_{\text{cable loss}} = \sqrt{\sigma_{11}^2 + \sigma_{21}^2} \tag{6}$$

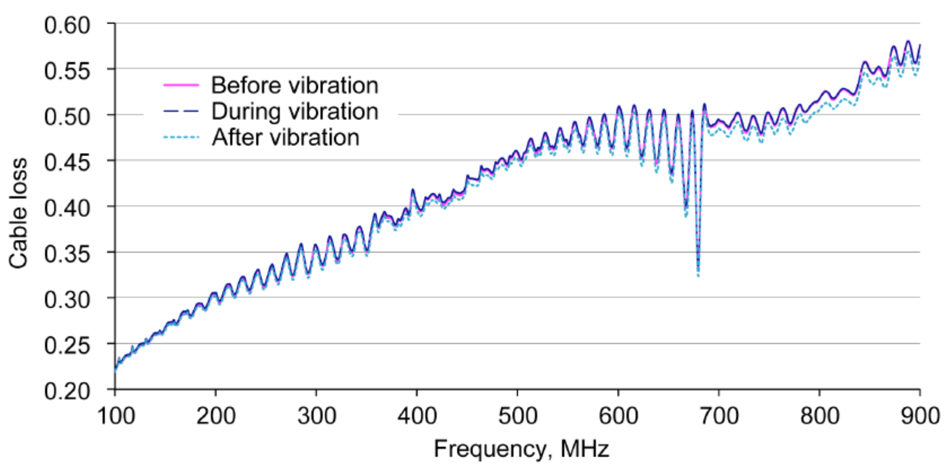

Figure 6.—Cable loss ($1 - S_{11} - S_{21}$) versus frequency for 8-m cable 8M1 before, during, and after vibration.

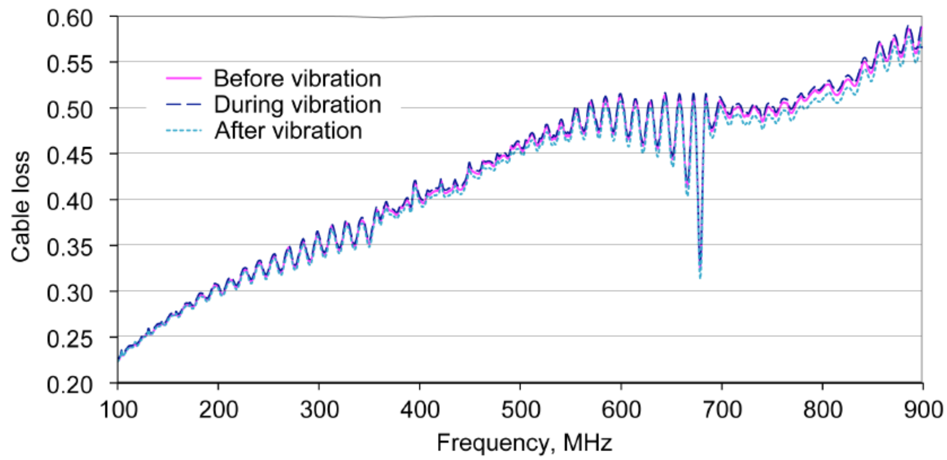

Figure 7.—Cable loss ($1 - S_{11} - S_{21}$) versus frequency for 8-m cable 8M2 before, during, and after vibration.

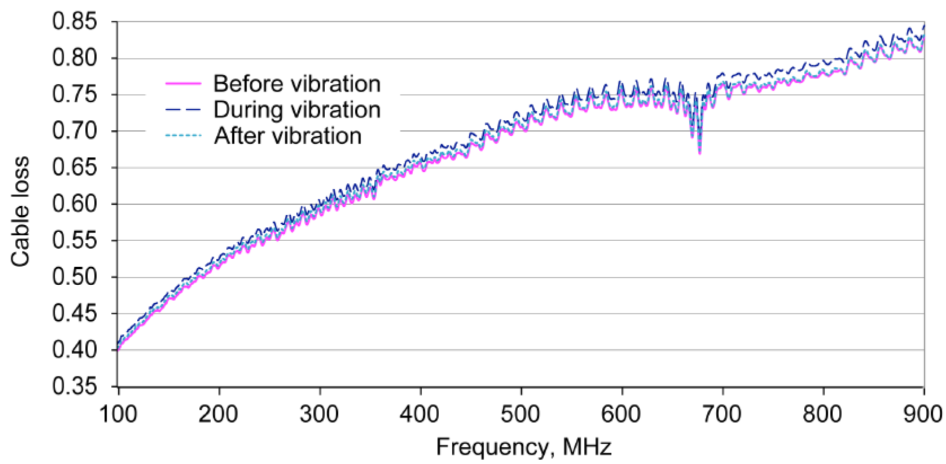

Figure 8.—Cable loss ($1 - S_{11} - S_{21}$) versus frequency for 16-m cable without bulkhead connector 16MNB between the 8-m cables 8M1 and 8M2 before, during, and after vibration.

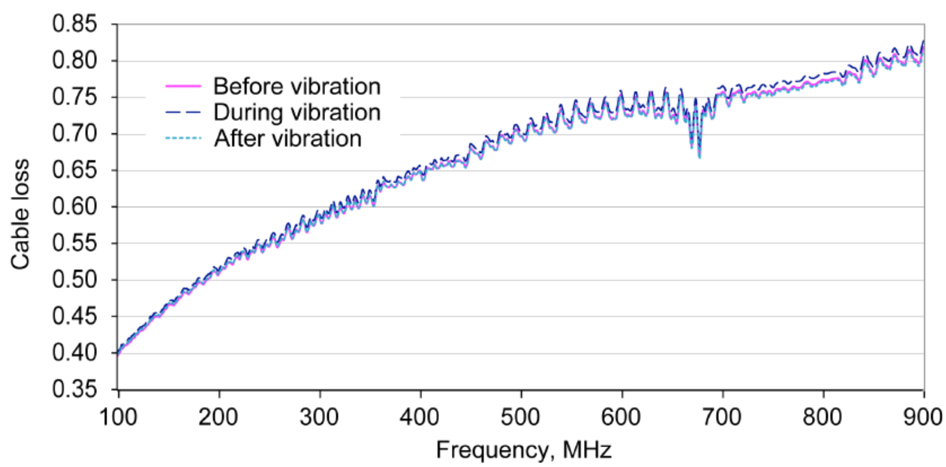

Figure 9.—Cable loss ($1 - S_{11} - S_{21}$) for 16-m cable with bulkhead connector 16MBH between the 8-m cables 8M1 and 8M2 versus frequency for before, during, and after vibration.

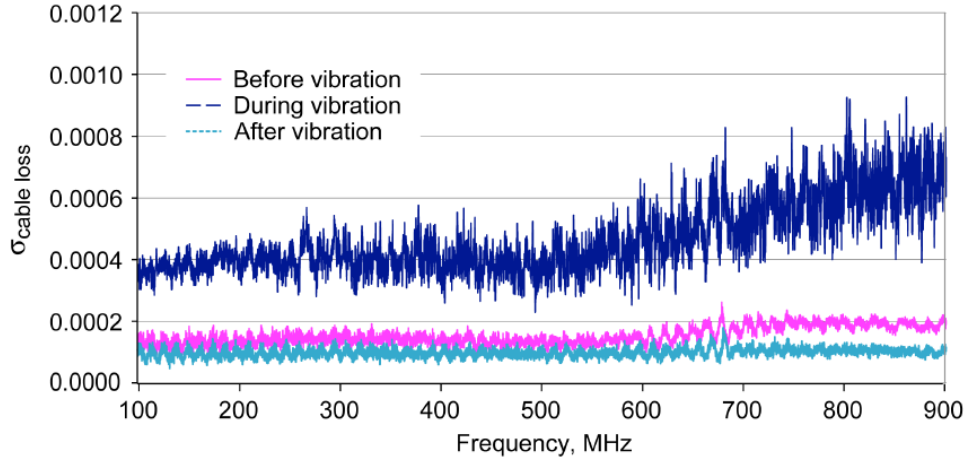

Figure 10.—Standard deviation in cable loss $\sigma_{cable\ loss}$ versus frequency in the 8-m cable 8M1 before, during, and after vibration.

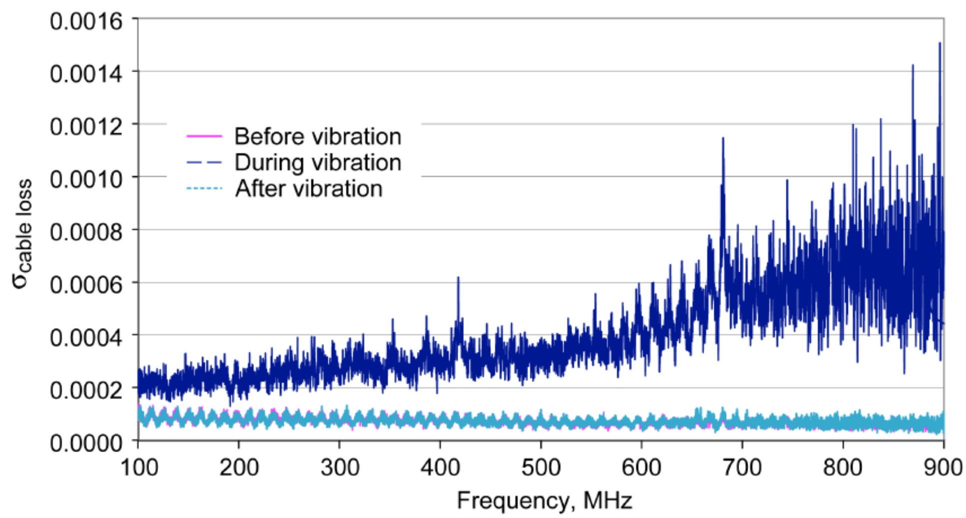

Figure 11.—Standard deviation in cable loss $\sigma_{cable\ loss}$ versus frequency in the 8-m cable 8M2 before, during, and after vibration.

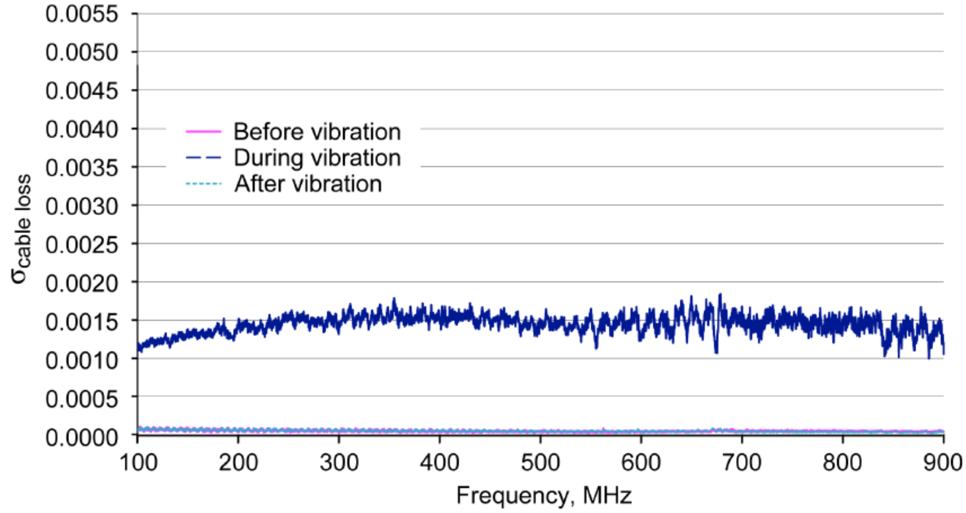

Figure 12.—Standard deviation in cable loss $\sigma_{cable\ loss}$ versus frequency for 16-m cable without bulkhead connector 16MNB between the two 8-m cables 8M1 and 8M2 for before, during, and after vibration.

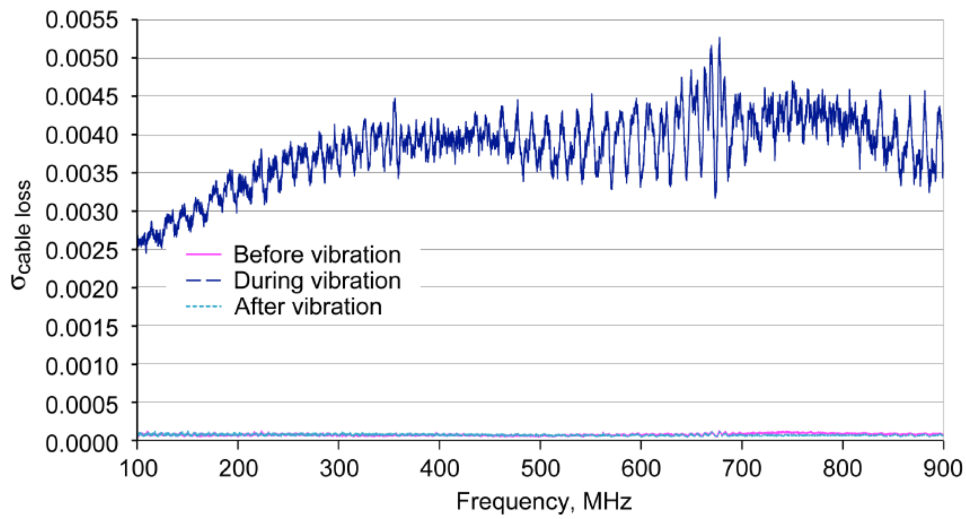

Figure 13.—Standard deviation in cable loss $\sigma_{cable\ loss}$ versus frequency for 16-m cable with bulkhead connector 16MBH between the two 8-m cables 8M1 and 8M2 for before, during, and after vibration.

It can be seen from Figures 10 to 13 that there is an increase in the uncertainty in cable loss $\sigma_{cable\ loss}$ during vibration compared to before or after vibrating the cables. Also a small consistent difference is observed in the $\sigma_{cable\ loss}$ between before and after vibrating the cables with the $\sigma_{cable\ loss}$ being slightly smaller after vibration than before. We do not have a definite reason for this effect, but will suggest there may be some type of relaxation of strain in the cable due to the vibration.

The $\sigma_{cable\ loss}$ for both the 8- and 16-m lengths before and after vibrations are very similar; however, the uncertainty in the cable losses for the 8- and 16-m length measurements during vibration are dramatically different.

The $\sigma_{\text{cable loss}}$ for the measurements of the 16-m cable is significantly higher than for the measurements of the 8-m cable. This is consistent with induced noise due to vibrations along the length of the cable. For the two 8-m cables there is not a significant difference in $\sigma_{\text{cable loss}}$ between similar measurements: those before, during, and after vibration of 8M1 and 8M2. Any changes in the magnitude of the noise of $\sigma_{\text{cable loss}}$ seen between Figures 10 and 11 are due to physical differences during the wrapping and securing of the cable onto the vibration platform.

The differences seen between measurements on cables 16MNB and 16MBH can be explained by the difference in how the two 8-m cables are connected to each other and held together.

What is significant in all of the measurements on the cable lengths of 8 and 16 m is the increase in $\sigma_{\text{cable loss}}$ when the cables are vibrated.

The $\sigma_{\text{cable loss}}$ is the RF-noise in the cables that must be known and used to determine the BER of the data sent down the cables. For the 8-m cable 8M1 in Figure 10 the $\sigma_{\text{cable loss}}$ increases by a factor of 3.5 to 6.5 when vibrated over either static magnitude, and in Figure 11 the factor for 8M2 is 2.5 to 7.5. For the 16-m length cables Figure 12 shows an increase in $\sigma_{\text{cable loss}}$ of a factor of 11 to15 during vibration as opposed to not vibrating for 16MNB; in Figure 13 the factor for 16MBH is 26 to 42. The difference between the two factors may be due to the bulkhead fitting being elevated above the vibration table with the cable connectors held in place by the fitting as opposed to the two 8-m cables being taped down to the vibration table.

For the same cables, the change Δ in the cable losses *CL* depicted in Figures 14 to 17 is defined as

$$\Delta = CL(\text{during vibration}) - \frac{1}{2}\left[CL(\text{after vibration}) + CL(\text{before vibration})\right] \tag{7}$$

From Figures 14 and 15 one sees that the Δ in the cable loss is similar in magnitude and trend. Although this is a small sample, it seems that the construction of the cables is consistent enough that the cables could be interchanged in the final construction of the communication system.

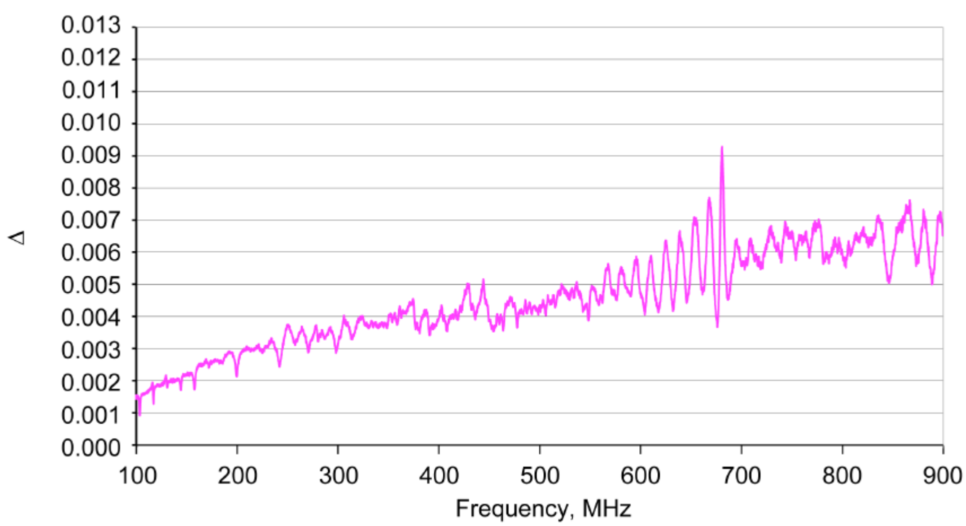

Figure 14.—Change in cable loss Δ versus frequency of 8-m cable 8M1, where Δ is cable loss during vibration minus the average of cable loss before and after vibration.

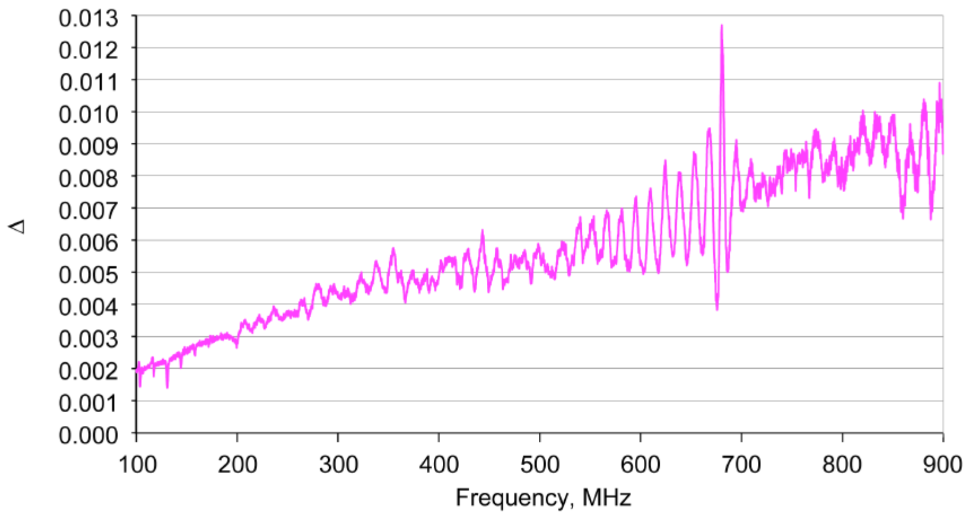

Figure 15.—Change in cable loss Δ versus frequency of 8-m cable 8M2, where Δ is cable loss during vibration minus the average of cable loss before and after vibration.

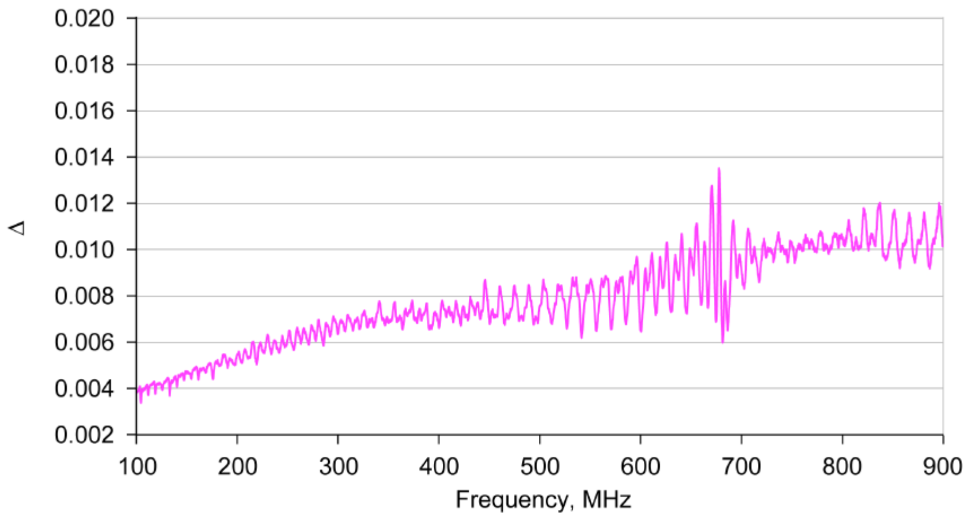

Figure 16.—Change in cable loss Δ versus frequency of 16-m cable without bulkhead fitting 16MNB, where Δ is cable loss during vibration minus the average of cable loss before and after vibration.

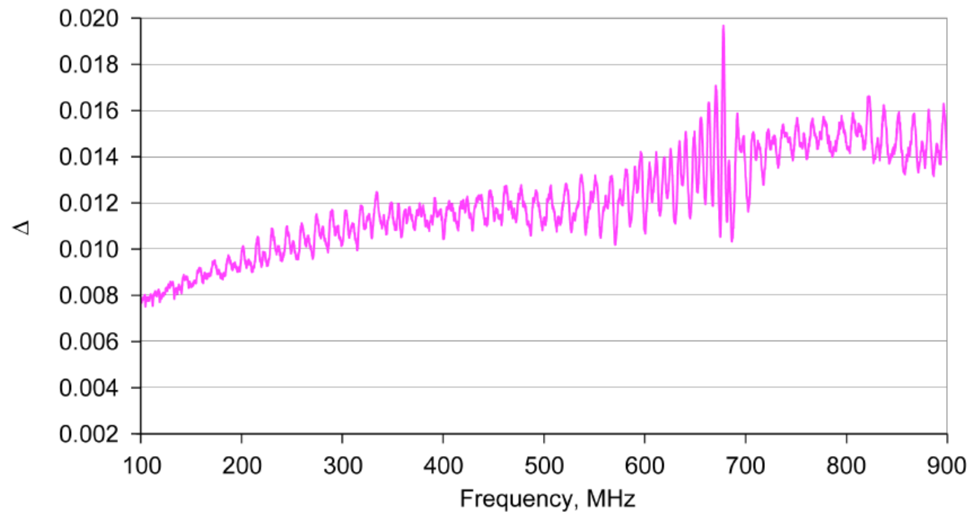

Figure 17.—Change in cable loss Δ versus frequency of 16-m cable with bulkhead fitting 16MBH, where Δ is the cable loss during vibration minus the average of cable loss before and after vibration.

The observed Δ in the cable losses due to vibration is small compared to the total loss observed for the cables. This means that the signal strength at the end of the cable does not vary much because of vibration. For example, the difference in the signal strength at the end of the cable for the 8M1 cable at 900 MHz will be 0.0065 (Fig. 14), whereas the total loss is 0.58 (Fig. 6).

From Figures 16 and 17 one sees that there is a consistent increase in Δ between cable 16MNB and 16MBH. That Δ in 16MBH is 0.004 greater that the Δ for 16MNB. Still the Δ is very small compared to the total losses in the cable whether it is being vibrated or not. For example, the difference in the signal strength at the end of the cable for the 16MNB cable at 900 MHz will be 0.011 (Fig. 16).

As one can see, the ratio of the difference in the cable losses divided by the average of the cable losses is the same for the two different lengths of cable (8 and 16 m).

Relating Cable Losses and Their Uncertainties to the BER

The previous report (Ref. 3) described how the BER from these measurements is dependent upon the increase in the noise in the signal due to vibration. This noise can be described by the standard deviation (σ_{21}) of S_{21}, which is defined as the ratio of the measured transmitted power at the end of the cable divided by the transmitted power at the beginning of the cable, or the transmission coefficient of the power. Also S_{21} is related to the voltage along the cable as given in Equation (8) where V is the voltage along the cable and V_0 is the voltage at the beginning of the cable,

$$S_{21}(x) = \frac{V^2(x)}{V_0^2} \tag{8}$$

where x is the distance along the cable (l is the overall length of the cable).

From the standard propagation of error method, the standard deviation of the voltage at the end of the cable $\sigma_V(l)$ is estimated from σ_{21}. That relationship is given in Equations (9) and (10):

$$\sigma_V(l) = \frac{V_0 \sigma_{21}(l)}{2\sqrt{S_{21}(l)}} \tag{9}$$

Then substituting Equation (8) for V_0 into Equation (9),

$$\sigma_V(l) = \frac{V(l)\sigma_{21}(l)}{2S_{21}(l)} \tag{10}$$

Once σ_V and V are determined at the end of the cable, the BER of the data is estimated using the Q function. For uncorrelated bits (i.e., no coding) x is simply V/σ_V .

For Orion the given acceptable BER for this communication line was 10^{-8}.

From the inverse Q function the number of standard deviations away from the average signal voltage level V at the end of the cable needed for a probability of 10^{-8} is 5.61. The detection voltage for a signal bit must be greater than $V + V_M$, where V_M is given below:

$$V_M(l) \geq 5.61\sigma_V(l) \tag{11}$$

The method to scale σ_{21} with the length of the cable is by recognizing that the noise in the voltage due to the ohmic losses of any passive device like the quadrax cable is proportional to the square root of the resistance R of the component. Since σ_{21} is the uncertainty in the S_{21}, which is a ratio of powers, then σ_{21} is proportional to R. Therefore,

$$\sigma_{21}(l_1) = \sigma_{21}(l_2)\left(\frac{l_1}{l_2}\right) \tag{12}$$

where l_1 is the length of the cable for the estimated σ_{21} and l_2 is the length of the cable for the measured σ_{21}. Equations (8), (9), and (11) imply

$$\left(\frac{V_M(l)}{V(l)}\right) \geq \frac{5.61}{2}\frac{\sigma_{21}(l)}{\sqrt{S_{21}(l)}}\left(\frac{V_0}{V(l)}\right) = 2.81\frac{\sigma_{21}(l)}{\sqrt{S_{21}(l)}}\left(\frac{V_0}{V(l)}\right) \tag{13}$$

To be able to attain a BER of 10^{-8} or better, the ratio of the voltage at the end of the cable to the input voltage must be greater than the value given in Equation (12). Equation (12) will give the limitation on the length of the cable possible for a BER of 10^{-8} or better for a particular voltage detection level. Of course the factor 5.61 in Equation (11) obtained from the inverse Q function will differ for a different BER needed.

To be able to extrapolate Equation (13) to different lengths of cable than what was measured, one needs to know the extinction coefficient for the cable loss. The voltage extinction coefficient beta β is given in Equation (14):

$$V(l) = V_0 10^{-\beta l} \tag{14}$$

Note that if the length of the cable is doubled,

$$\frac{V(2l)}{V_0} = \left(\frac{V(l)}{V_0}\right)^2 \tag{15}$$

Combining terms from Equations (12), (14), and (15) into Equation (13) and taking the ratios of V_M/V at the actual measured length l_A (8 or 16 m) and the extrapolated length l_E needed for Orion (l_E = 25 m) one obtains

$$\left(\frac{V_M(l_E)}{V(l_E)}\right) \geq 2.81\frac{\sigma_{21}(l_A)}{\sqrt{S_{21}(l_A)}}\left(\frac{l_E}{l_A}\right)10^{\beta(l_E - l_A)} \tag{16}$$

where l_A is the length of the measured cables, either 8 or 16 m, and l_E is the length of cable needed for the Orion SM, 25 m.

The β can be calculated from S_{21} by remembering that S_{21} is proportional to the square of the voltage. This gives a function of S_{21} versus the length of the cable:

$$S_{21}(l) = S_{21}(0)\cdot 10^{-2\beta l} = S_{21}(0)\cdot 10^{-\alpha l} \tag{17}$$

$$S_{21}(0) = 1 - S_{11} \tag{18}$$

where S_{11} is the reflection coefficient for the power measurement and α is the extinction coefficient for the cable loss.

Therefore,

$$\alpha = \frac{1}{l}\log_{10}\left(\frac{1 - S_{11}}{S_{21}(l)}\right) \tag{19}$$

Data from the 16-m cable were used to predict the noise level and the BER at a vibration level of 32g for a 25-m cable with the highest fundamental frequency of 625 MHz and its first harmonic at 1250 MHz. For this case l_A = 16 m and l_E = 25 m. Substituting Equation (19) into Equation (16) results in

$$\left(\frac{V_M(l_E)}{V(l_E)}\right) \geq \frac{2.81\sigma_{21}(l_A)}{\sqrt{S_{21}(l_A)}}\left(\frac{l_E}{l_A}\right)\left(\frac{1 - S_{11}}{S_{21}(l_A)}\right)^{\frac{1}{2}\left(\frac{l_E}{l_A} - 1\right)} \tag{20}$$

Substituting 16 for l_A and 25 for l_E in Equation (20) at a given frequency gives

$$\left(\frac{V_M(25)}{V(25)}\right) \geq \frac{2.81\sigma_{21}(16)}{\sqrt{S_{21}(16)}}\left(\frac{25}{16}\right)\left(\frac{1 - S_{11}}{S_{21}(16)}\right)^{9/32} \tag{21}$$

The ratio of the voltage of the signal at the end of the cable to the voltage at the beginning of the cable that is needed to obtain a BER of 10^{-8} for the cables measured in this study is shown in Figures 18 to 21 as a function of frequency. Also in these figures there has been a simple polynomial fit versus frequency for the measurements during vibration.

In Figure 22 the graphs of V_M/V before vibration are plotted together for comparison. The noise V_M/V for all four cables is extremely small, and it appears that the noise does not depend on the cable length. When the cables are not vibrated, achieving a BER of 10^{-8} is very easy because for low-voltage differential signals (LVDS) V is typically 1.35 V. With the signal level at 1.35 V the standard deviation of the voltage at the end of the 16-m cable corresponds to approximately 1.1 mV or greater at 900 MHz using the V_M/V from Figure 22. So the difference between the mean of the signal level and the detection threshold of the instrument only needs to be 1.1 mV or greater for a BER better than 10^{-8}.

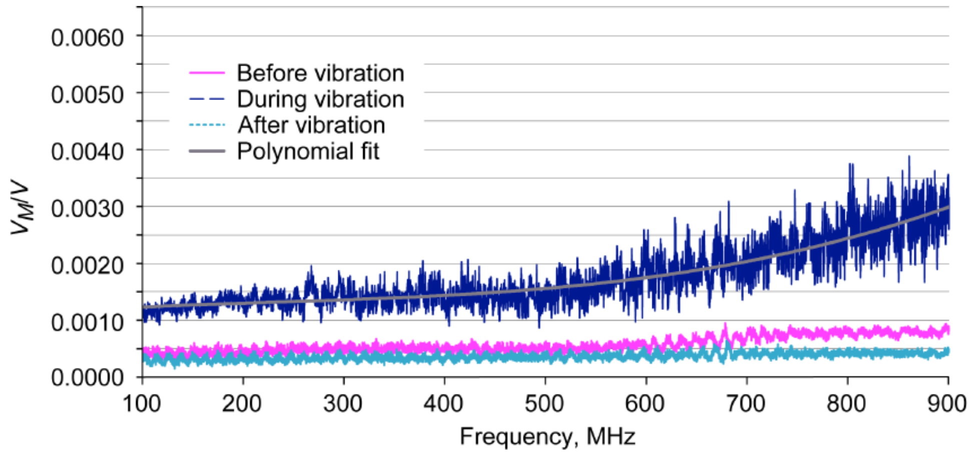

Figure 18.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for 8-m cable 8M1 that is necessary to obtain a bit-error rate (BER) of 10^{-8} or better before, during, and after vibration. The polynomial fit of the data is given by $y = 4{\cdot}10^{-30}\,x^3 - 3{\cdot}10^{-21}\,x^2 + 1{\cdot}10^{-21}\,x + 0.0011$, and the coefficient of determination $R^2 = 0.7954$.

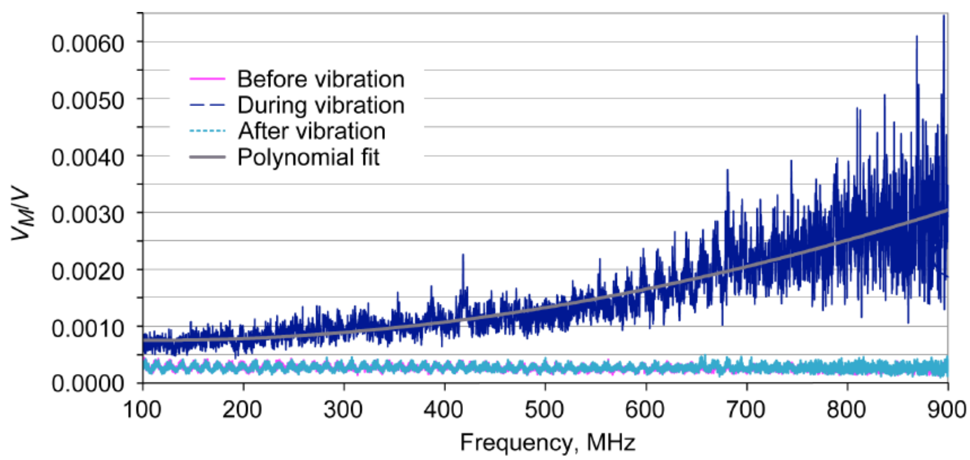

Figure 19.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for 8-m cable 8M2 that is necessary to obtain a bit-error rate (BER) of 10^{-8} or better before, during, and after vibration. The polynomial fit of the data is given by $y = -2{\cdot}10^{-31}\,x^3 + 4{\cdot}10^{-21}\,x^2 - 8{\cdot}10^{-13}\,x + 0.0008$, and the coefficient of determination $R^2 = 0.7944$.

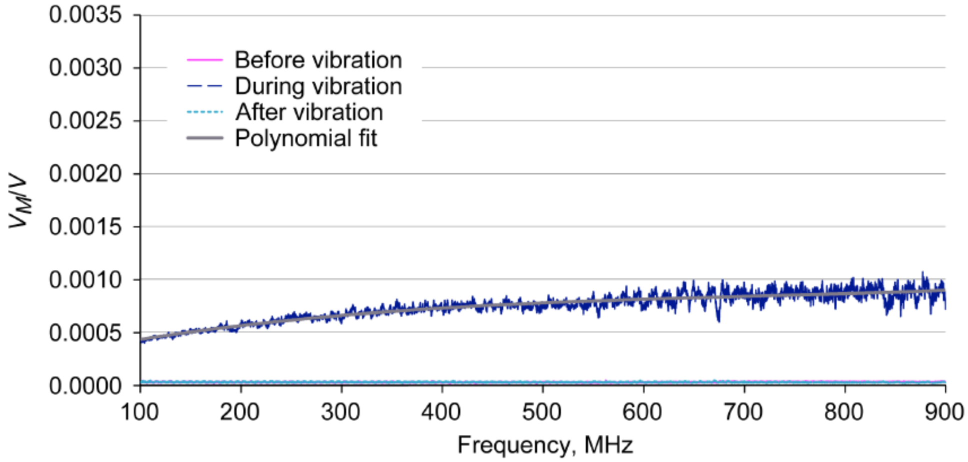

Figure 20.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for 16-m cable without bulkhead connector 16MNB that is necessary to obtain a bit-error rate (BER) of 10^{-8} or better before, during, and after vibration. The polynomial fit of the data is given by $y = 1 \cdot 10^{-29} x^3 - 2 \cdot 10^{-20} x^2 + 2 \cdot 10^{-11} x + 0.0026$, and the coefficient of determination $R^2 = 0.8819$.

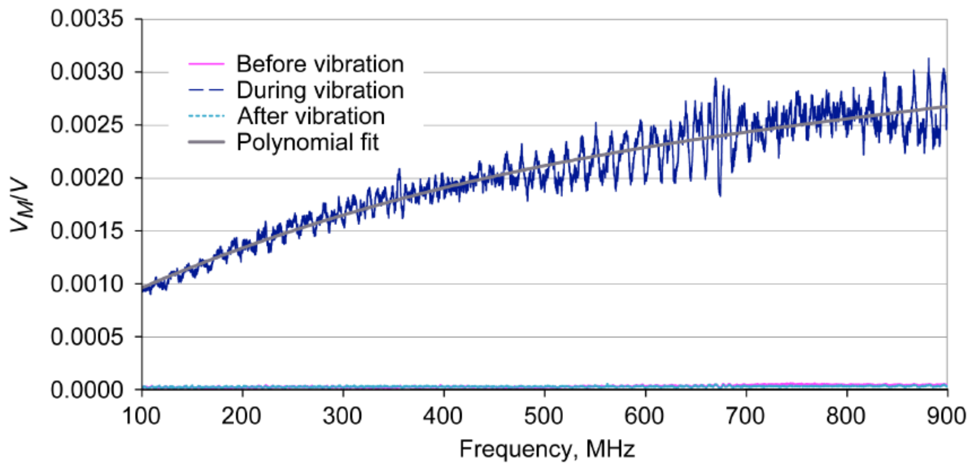

Figure 21.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for 16-m cable with bulkhead connector 16MBH that is necessary to obtain a bit-error rate (BER) of 10^{-8} or better before, during, and after vibration. The polynomial fit of the data is given by $y = 2 \cdot 10^{-29} x^3 - 4 \cdot 10^{-20} x^2 + 5 \cdot 10^{-11} x + 0.0052$, and the coefficient of determination $R^2 = 0.9298$.

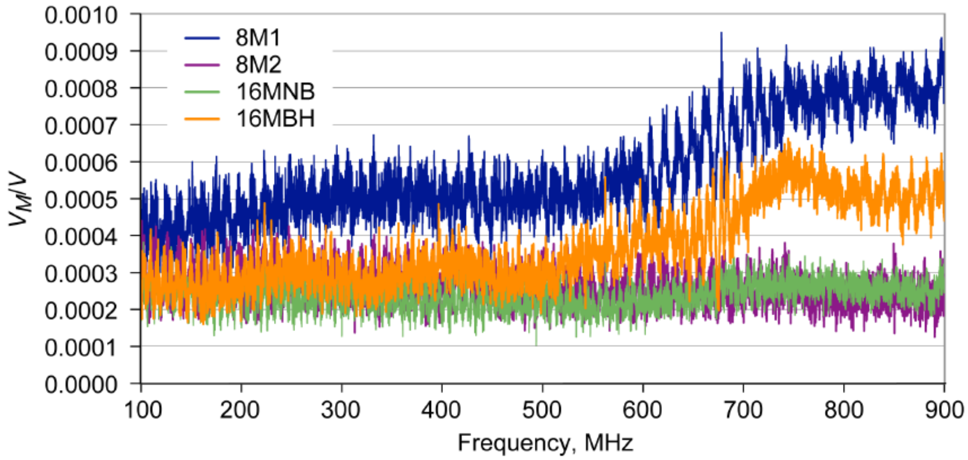

Figure 22.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for the four cables (8M1, 8M2, 16MNB, and 16MBH) before vibration.

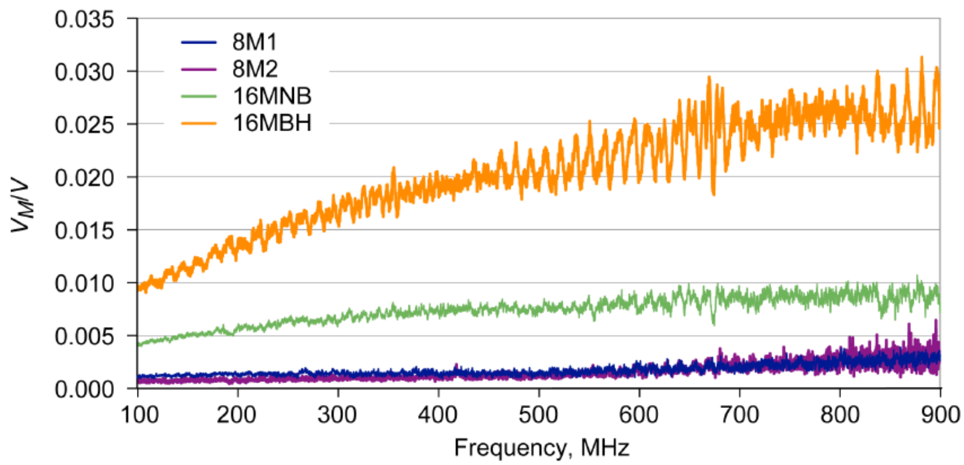

Figure 23.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for the four cables (8M1, 8M2, 16MNB, and 16MBH) during vibration.

In Figure 23, V_M/V for the four cables from Figures 18 to 21 during vibration is compared. As it can be seen between Figures 22 and 23, V_M/V is much greater during vibration than when the cables are not being vibrated.

For LVDS, the difference between the mean of the signal level and the detection threshold of the instrument needs to be 36 mV or greater at 900 MHz for a BER better than 10^{-8} for a 16-m cable with the bulkhead fitting and only approximately 13 mV for the 16-m cable without the bulkhead fitting.

Estimating V_M/V for the Orion Cables

Having established a methodology to determine the ratio of the standard deviation needed for a particular BER to the mean signal level voltage in a cable and how to extrapolate this ratio to different frequencies and different cable lengths, the standard deviation of the mean voltage for the Orion cable is now estimated at the needed length and at 1250 MHz. To do this estimate the cable length is extrapolated from 16 to 25 m, and V_M/V versus frequency is extrapolated to 1250 MHz.

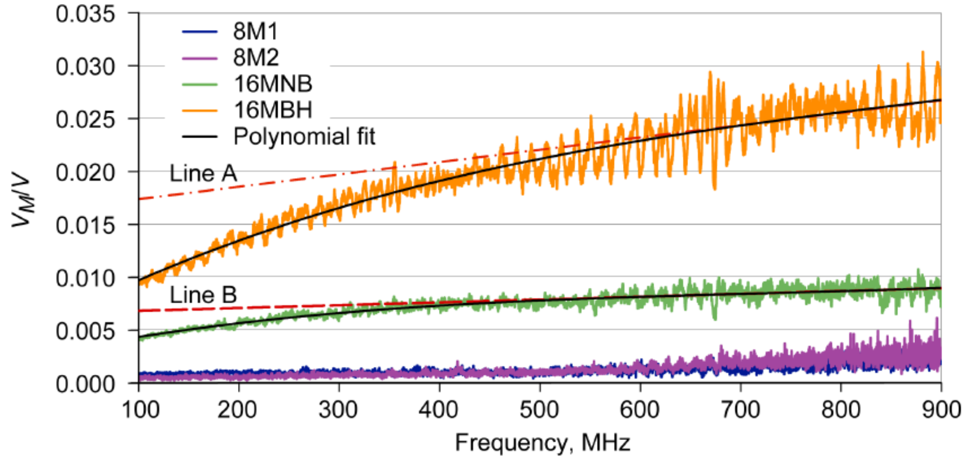

Figure 24.—The ratio of voltage of the signal at the end to that at the beginning of the cable V_M/V versus frequency for the four cables (8M1, 8M2, 16MNB, and 16MBH) before vibration during vibration with polynomial fits to 16MBH ($y = 2{\cdot}10^{-29}\,x^3 - 4{\cdot}10^{-20}\,x^2 + 5{\cdot}10^{-11}\,x + 0.0052$) with the coefficient of determination $R^2 = 0.9298$ and 16MBN ($y = 1{\cdot}10^{-29}\,x^3 - 2{\cdot}10^{-20}\,x^2 + 2{\cdot}10^{-11}\,x + 0.0026$ with $R^2 = 0.8819$), and the tangential lines to these polynomial fits.

In Figures 18 to 21, the data during vibration was fitted to a polynomial as given in those figures. Then for cables 16MNB and 16MBH a linear line was made tangent to the polynomial-fitted curve at the upper frequency region. The data, the fitted curves to the data, and the tangential line to these fitted curves are depicted in Figure 24.

To obtain the needed V_M/V for the 25-m Orion cable at 1250 MHz Equation (21) is rewritten:

$$\left(\frac{V_M}{V}\right)(25\ \mathrm{m}, 1250\ \mathrm{MHz}) \geq \left(\frac{V_M}{V}\right)(16\ \mathrm{m}, 1250\ \mathrm{MHz})\left(\frac{25}{16}\right)\left(\frac{1 - S_{11}(1250\ \mathrm{MHz})}{S_{21}(16\ \mathrm{m}, 1250\ \mathrm{MHz})}\right)^{9/32} \tag{22}$$

The equation of the fitted line for the 16MBH cable in Figure 24 is

$$\frac{V_M}{V}(f) = 1.17\times 10^{-11}\, f + 0.0162 \tag{23}$$

where f is the frequency in Hz. Evaluating Equation (23) for f at 625 and 1250 MHz results in $V_M/V(f)$ equaling 0.024 and 0.031, respectively.

The equation of the line for the 16MNB cable is

$$\frac{V_M}{V}(f) = 2.68\times 10^{-12}\, f + 0.0065 \tag{24}$$

Evaluating this expression for f at 625 and 1250 MHz results in V_M/V equaling 0.0082 and 0.0099, respectively.

Because the value of V_M/V is based on the tangential line to the fitted curve at 625 MHz, its value is almost identical to the value of $V_M/V\,(f)$ for the value calculated from the polynomial in Figure 26; therefore, the straight line Equations (23) and (24) for V_M/V (625 MHz) can be used instead of the polynomial equation for both 16MBH and 16MNB cables.

Extinction Coefficient Alpha α and S_{11}

The extinction coefficient α for S_{21} that is given in Equation (19) is plotted in Figure 25 for cable 8M1, and a straight line is fitted to the data. This line was used to extrapolate α to 1250 MHz. It is this value of extrapolated α that was used in the subsequent calculations.

The fitted line to the data in Figure 25 is

$$\alpha(f) = 4.75 \times 10^{-11} f + 0.0092 \tag{25}$$

This results in a value of 0.039 at 625 MHz and 0.069 at 1250 MHz.

In Figure 26 the reflection coefficient S_{11} is plotted along with the fitted line to the curve. The peak in the S_{11} between 650 and 700 MHz is due to the property of the baluns used in the measurement. One can see the S_{11} is less than about 0.5 percent over the entire frequency range when the peak to the baluns is ignored.

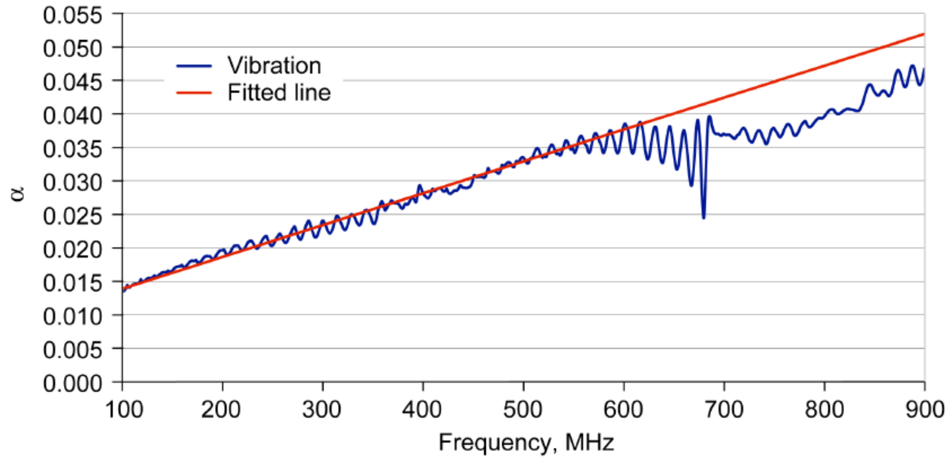

Figure 25.—Extinction coefficient α for reflection coefficient S_{11} and fitted line to α versus frequency for 8-m cable 8M1 before vibration.

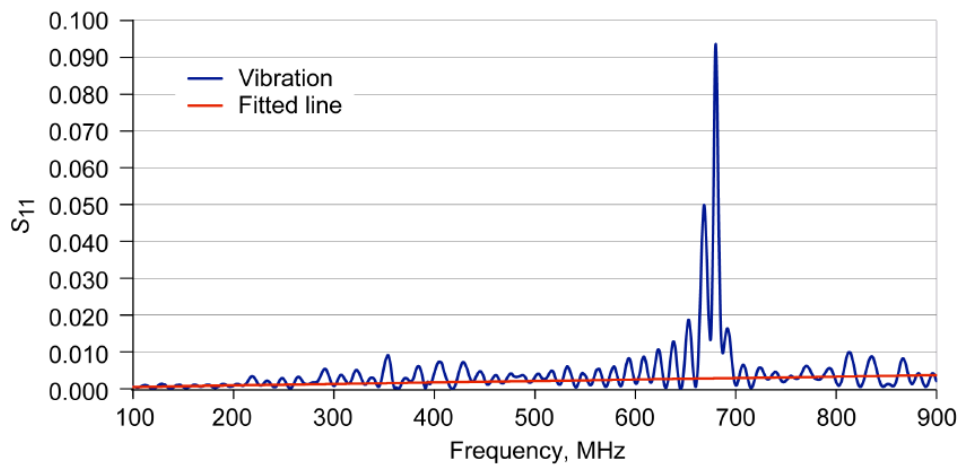

Figure 26.—Reflection coefficient S_{11} and fitted line to S_{11} versus frequency for 8-m cable 8M1 before vibration.

A straight line is fitted to the S_{11} data for cable 8M1 in Figure 26. This fitted line to the data in Figure 26 is given in Equation (26):

$$S_{11}(f) = 4.00 \times 10^{-12} f + 0.0001 \tag{26}$$

This results in a value of 0.0026 at 625 MHz and 0.0051 at 1250 MHz.

Extrapolating the measured value to cable lengths of 25 m and 1250 MHz requires knowledge of S_{11} and s at 1250 MHz. The transmission coefficient S_{21} for 25 m at both 625 and 1250 MHz from Equations (17), (18), (25), and (26) is now calculated:

$$S_{21}(25\text{m}, 625\text{ MHz}) = (1 - 0.0026)10^{-0.039(25)} = 0.11\text{, which is –9.76 dB} \tag{27a}$$

$$S_{21}(25\text{m}, 1250\text{ MHz}) = (1 - 0.0051)10^{-0.069(25)} = 0.019\text{, which is –17.27 dB} \tag{27b}$$

The equations versus frequency for all the cables measured are given in Table I including those in Figures 25 and 26. Table I also includes the estimate of S_{21} for a length of 25 m and at frequencies of 625 and 1250 MHz. In Table I, *f* is given in megahertz.

It is seen in Table I the extinction coefficient and the reflection coefficient for each cable before, during, and after vibration are approximately the same except for cable 16MBH, which is the cable with the bulkhead fitting. It is not unreasonable to suggest that the bulkhead fitting increase loss down the cable when it is being vibrated since the bulkhead fitting introduces a moment arm of approximately 4 cm.

To determine the BER for quadrax cables with a length of 25 m and at 625 and 1250 MHz while being vibrated at 32g the S_{21} must be converted into a voltage ratio. This voltage ratio is the minimal voltage difference between the signal voltage at the end of the cable, and the detection voltage that determines if a bit is a “one” or a “zero.”

For cables 16MBH and 16MNB Equations (21) and (23) along with results from Table I are used to calculate V_M/V at the desired frequency and length. The results are summarized in Table II. An example of the calculation method for the 16MBH cable at a frequency of 625 MHz is presented:

$$\frac{V_M}{V}(25\text{ m}, 625\text{ MHz}) = 0.024\left(\frac{25}{16}\right)\left[\frac{1 - S_{11}(625\text{ MHz})}{S_{21}(16\text{ m}, 625\text{ MHz})}\right]^{9/32} = 0.0375\left(\frac{1 - 0.0026}{0.094}\right)^{0.28125} = 0.073 \tag{28}$$

Thus the voltage above the detection voltage divided by the input voltage must be at least 7.3 percent.

TABLE I.—CABLE PROPERTIES AND TRANSMISSION CHARACTERISTICS

Vibration	Cable	Extinction coefficient, $\alpha(f)$	Reflection coefficient, $S_{11}(f)$	Transmission coefficient at f = 625 MHz,[a] S_{21}, dB	Transmission coefficient at f = 1250 MHz,[a] S_{21}, dB
Before	8M1	$4.75 \cdot 10^{-11} f + 0.0092$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.27
	8M2	$4.80 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.16
	16MNB	$4.80 \cdot 10^{-11} f + 0.0094$	$5.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.14
	16MBH	$4.80 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–10.01	–17.52
During	8M1	$4.70 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.02
	8M2	$4.80 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.16
	16MNB	$4.80 \cdot 10^{-11} f + 0.0094$	$5.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.16
	16MBH	$5.00 \cdot 10^{-11} f + 0.01$	$4.00 \cdot 10^{-12} f + 0.0001$	–10.26	–18.27
After	8M1	$4.60 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.51	–16.77
	8M2	$4.70 \cdot 10^{-11} f + 0.0094$	$4.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.02
	16MNB	$4.80 \cdot 10^{-11} f + 0.0095$	$5.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.14
	16MBH	$4.80 \cdot 10^{-11} f + 0.0094$	$5.00 \cdot 10^{-12} f + 0.0001$	–9.76	–17.14

[a]For cable length of 25 m.

TABLE II.—VALUE OF V_M/V AT 25 m CABLE LENGTH

Cable	625 MHz	1250 MHz
16MBH	0.073	0.158
16MNB	0.024	0.047

The 32g-induced voltage noise V_M/V (625 MHz) is between 2.4 and 7.3 percent; the corresponding values at 1250 MHz are between 4.7 and 15.8 percent. Therefore, for a BER of 10^{-8}, the signal level must be $0.073V$ from the detection voltage that separates a one from a zero at 625 MHz while it must $0.158V$ at 1250 MHz.

Results

The evaluation of α, S_{11}, and S_{21} at 625 MHz is given in Table III and at 1250 MHz is given in Table IV.

As can be seen in Tables III and IV the extinction coefficient a and the reflection coefficient S_{11} double as the frequency is doubled. The transmission coefficient S_{21} though increases by 7 to 8 dB as the frequency is doubled. This is consistent with both α and S_{11} doubling.

TABLE III.—ESTIMATIONS OF a, S_{11}, AND S_{21} FOR 25 m OF 8M1, 8M2, 16MNB, AND 16MBH CABLES AT 625 MHz AND RANDOM VIBRATION LEVELS OF 32g BEFORE, DURING, AND AFTER VIBRATION

Cable	Extinction coefficient, a, m^{-1}			Reflection coefficient, S_{11}			Transmission coefficient, S_{21}, dB		
	Before	During	After	Before	During	After	Before	During	After
8M1	0.039	0.039	0.038	0.0026	0.0026	0.0026	–9.76	–9.76	–9.51
8M2	0.039	0.039	0.039	0.0026	0.0026	0.0026	–9.76	–9.76	–9.76
16MNB	0.040	0.039	0.039	0.0032	0.0032	0.0032	–9.76	–9.76	–9.76
16MBH	0.040	0.041	0.040	0.0026	0.0026	0.0026	–10.01	–10.26	–10.01

TABLE IV.—ESTIMATIONS OF a, S_{11}, AND S_{21} FOR 25 m of 8M1, 8M2, 16MNB, AND 16MBH CABLES AT 1250 MHz AND RANDOM VIBRATION LEVELS OF 32g BEFORE, DURING, AND AFTER VIBRATION

Cable	Extinction coefficient, a, m^{-1}			Reflection coefficient, S_{11}			Transmission coefficient, S_{21}, dB		
	Before	During	After	Before	During	After	Before	During	After
8M1	0.069	0.068	0.067	0.0051	0.0051	0.0051	–17.27	–17.02	–16.77
8M2	0.069	0.069	0.068	0.0051	0.0051	0.0051	–17.16	–17.16	–17.02
16MNB	0.069	0.069	0.069	0.0064	0.0064	0.0064	–17.14	–17.14	–17.14
16MBH	0.070	0.073	0.071	0.0051	0.0051	0.0051	–17.52	–18.27	–17.77

Conclusions

The proposed Orion cables, in 25-m lengths, when going through a single bulkhead connection while being randomly vibrated to 32g, are expected to have a loss of 10.3 dB at 625 MHz (fundamental frequency) and 18.3 dB at 1250 MHz (first harmonic). We have determined the extinction coefficient and the reflection coefficient of the quadrax cables versus frequency along with estimating the transmission coefficient at 625 and 1250 MHz for a 25-m cable.

The 10.3 dB estimated cable loss at 25 m and 625 MHz exceeds the IEEE Standard 802.3 Clause 39 recommended 8.8 dB1. It is incumbent upon the designers to take these variations into account.

Most importantly we have determined the voltage ratio of noise to input signal voltage that must be met to achieve a bit error rate (BER) of 10^{-8}. For a typical input voltage of 1.35 V the signal voltage about the detection threshold must be at least 216 mV for a BER of 10^{-8} during launch.

Future Work

Our research only involved a very small sample of these wires. A larger sample size would result in better fidelity and the ability to characterize the quadrax connectors for scenarios where link budgets are tight. In addition to the analog method used here, a digital method should be utilized with a digital sequence generator and a bit error rate tester.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
An experiment was performed to determine the degradation in the bit-error-rate (BER) in the high-data-rate cables chosen for the Orion Service Module due to extreme launch conditions of vibrations with a magnitude of 60g. The cable type chosen for the Orion Service Module was #8 quadrax cable. The increase in electrical noise induced on these #8 quadrax cables was measured at the NASA Glenn vibration facility in the Structural Dynamics Laboratory. The intensity of the vibrations was set at 32g, which was the maximum available level at the facility. The cable lengths used during measurements were 1, 4, and 8 m. The noise measurements were done in an analog fashion using a performance network analyzer (PNA) by recording the standard deviation of the transmission scattering parameter S_{21} over the frequency range of 100 to 900 MHz. The standard deviation of S_{21} was measured before, during, and after the vibration of the cables at the vibration facility. We observed an increase in noise by a factor of 2 to 6. From these measurements we estimated the increase expected in the BER for a cable length of 25 m and concluded that these findings are large enough that the noise increase due to vibration must be taken in to account for the design of the communication system for a BER of 10^{-8}.

15. SUBJECT TERMS
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