Simulation Diagnostics of Multiple Discontinuities in a Microwave Coaxial Transmission Line

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Abstract—**Multiple discontinuities in microwave transmission lines can cause unusual reflection and transmission loss characteristics as functions of frequency. This article presents a method for developing models that simulate return loss and insertion loss data measured over a broad band of frequencies. The overall cable is modeled as a coaxial transmission line consisting of shunt susceptance discontinuities separated by line lengths. A nonlinear least-squares fit is then performed between theoretical data (from the model) and experimental data. When this method was applied to modeling discontinuities in a slightly damaged S-band antenna cable, excellent agreement between theory and experiment was obtained over a frequency range of 1.70–2.85 GHz.**

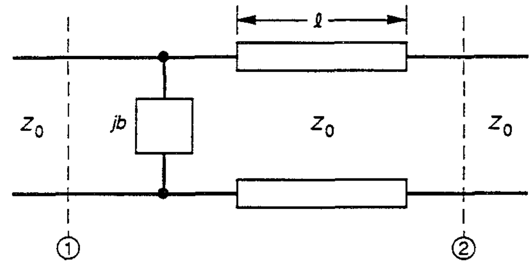

Fig. 1. Basic network used in cable model.

I. INTRODUCTION

THE GALILEO spacecraft, launched on October 18, 1989, is currently on its interplanetary journey to encounter Jupiter in December, 1995. Prior to launch, Galileo underwent environmental testing in the Space Simulator at the Jet Propulsion Laboratory (JPL). After these tests, it was discovered that the S-band output power had dropped about 0.2 dB at the transmit frequency of 2.295 GHz. More alarming were the radical changes observed in the insertion loss characteristics of the S-band antenna cable. Instead of the small peak-to-peak sinusoidal variations seen on pre-environmental test data, numerous nonperiodic humps and valleys (of unusual amplitudes) were seen on the post-environmental test data over a frequency range of 1.7–2.85 GHz [1].[1]

This article presents the methodology used to develop models of the antenna cable,[2] which was suspected of having been damaged by environmental testing. It is shown that the final model, obtained with the aid of a nonlinear least-squares fit (NLSF) program, provided theoretical data that gave excellent agreement with all available experimental data over the entire frequency range.

II. METHODOLOGY

The first step in the modeling procedure was to measure S-parameters of the suspected-damaged cable over a frequency range centered at the particular frequency of interest. From the measured S-parameter data, return loss time domain plots were generated showing the approximate locations of discontinuities in the cable. The return-loss magnitude information on the time domain plots was used to synthesize equivalent circuit elements of individual discontinuities. Then the overall cable was modeled as a coaxial transmission line consisting of individual shunt susceptances (representing discontinuities) separated by different lengths of lossy coaxial line sections. The relative dielectric constant and attenuation constant of the line sections were taken into account.

Fig. 1 shows the basic network used in the modeling work. The elements of the network are a capacitive shunt susceptance followed by a length of lossy transmission line. The S-parameters for this basic network are

$$[N] = \frac{1}{2+jb}\begin{bmatrix} -jb & 2e^{-\gamma\ell} \\ 2e^{-\gamma\ell} & -jbe^{-2\gamma\ell} \end{bmatrix} \tag{1}$$

where b is the normalized shunt susceptance, γ is the complex propagation constant, and ℓ is the line length.

For a *Constant Capacitance Model*

$$b = 2\pi f C Z_0 \tag{2}$$

where f is the frequency in hertz, C is the capacitance in farads, and Z_0 is the transmission line characteristic impedance in ohms.

For a *Constant Shunt Capacitive Susceptance Model,* b is a constant. The nominal value of b for both models can be obtained from the relationship, derived from (1), of

$$b = \frac{2|N_{11}|}{\sqrt{1-|N_{11}|^2}} \tag{3}$$

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[1] This article contains additional details of the earlier modeling work. Applicable mismatch error and group delay equations are presented in the appendices.

[2] This cable (referred to as the S-band cable for Low-Gain Antenna #2) was used on board Galileo during the early part of the spacecraft's interplanetary flight to Jupiter.

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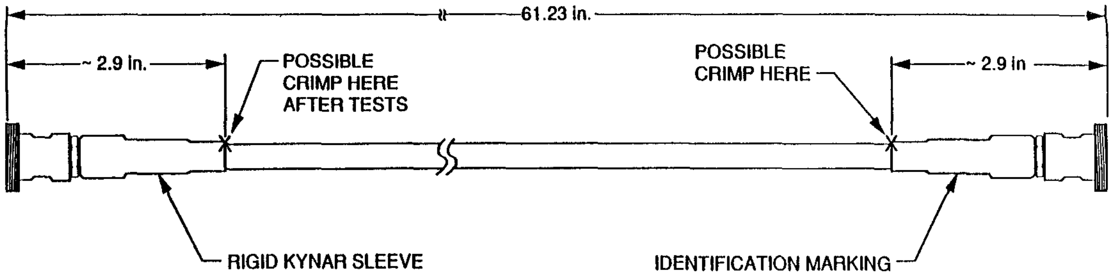

Fig. 2. Galileo S-band cable outer dimension detail.

where

$$|N_{11}| = 10^{-(RL_1/20 - A_{dB}/10)} \tag{4}$$

and RL_1 is the positive decibel return loss value (at the discontinuity location on the time domain plot as seen looking into port 1), and A_{dB} is the positive decibel value for the transmission line loss between the discontinuity and port 1.

After calculating the S-parameters of individually modeled cable discontinuities and line separations using (1), the next step is to cascade the individual basic networks and calculate the overall S-parameters of the cable. After deriving the overall S-parameters, the insertion loss (also referred to as attenuation) of the cable is calculated at each frequency from

$$L_{dB} = 20 \log_{10} |S_{21}| \tag{5}$$

where S_{21} is the overall transmission coefficient of the cascaded basic networks of the cable.

This procedure led to the desired theoretical data set. The parameter S_{12} need not be considered since for a passive two-port network, $S_{12} = S_{21}$. Theoretical return loss data sets were obtained by converting the overall S_{11} and S_{22} data into decibels. For this modeling procedure, the theoretical return loss data sets were not actually used in the least-squares fitting process, but were used later for comparisons to experimental data.

The subject of modeling discontinuities is extensive and is treated elsewhere [2]–[7]. For purposes of this article, only the simple types of discontinuities (described above) are considered.

III. Computer-Aided NLSF Procedure

If a physical phenomenon associated with experimental data can be modeled mathematically (no matter how involved and complex the mathematical formulas), then the modeled theoretical data can almost always be best-fitted to experimental data through the use of an NLSF program. Most NLSF programs are easy to use. Variance, correlation coefficients, and standard deviations can be computed from the residuals of the nonlinear curve-fitting process.

For most NLSF programs, the user provides 1) the experimental data set, 2) the subroutine program to calculate the theoretical values for the mathematical model, and 3) estimates of the nominal or starting values of the parameters to be best-fitted. More advanced NLSF programs allow bounds to be specified so that the best-fitted parameter values will stay within physical realizable limits. From the provided input data and subroutines, the NLSF program does the necessary number of iterations and computations to find the parameter values that give the best fit (using a least-squares convergence criterion) between theoretical and experimental values.

The particular public-domain NLSF program [8],[1] used to obtain the results described in this article, can be run on a personal computer. For the cable problem being studied, the theoretical values given by (5) were computed in a FORTRAN subroutine. The parameters, to be adjusted for best fit by the NLSF program, were specified to be 1) the discontinuity magnitudes (in terms of shunt susceptance or capacitance values) and 2) the line lengths separating the discontinuities. Even though the distances between the discontinuities were allowed to be adjusted within specified bounds, the program was written so that the resulting overall length of the cable for the model had to be equal to the actual physical length of the cable.

IV. Results

Prior to obtaining the final model, Models 1 and 2 were developed without the aid of the NLSF Program. Although Model 1 was unsuccessful, Model 2, described in [1], was partially successful in that it provided insight into the probable causes of the radical changes in insertion loss as a function of frequency. Model 3, developed with the aid of the NLSF program, was based on modeling each discontinuity with a constant shunt capacitance (see (2)). As described in [1], Model 3 provided an excellent theoretical fit with some, but not all, of the experimental data that was available.

Model 4, the final model, was also developed with the aid of the NLSF program and the previously described modeling procedure. It was based upon representing the discontinuities as *constant capacitive shunt susceptance* values over the frequency range of interest (see (3)). These discontinuities could be deep creases or crimps on the outer diameter of the cable. Such discontinuities can be created in practice by bending the cable against the edge of a cable clamp or the edge of a Kynar sleeve (Fig. 2).

The overall equivalent circuit and locations of the discontinuities along the cable are shown in Fig. 3. Model 4 is

[1] The particular NLSF program used for the JPL modeling work was a later version of the original release of NL2SOL by D. Gay and L. Kaufman, now at AT&T, Bell Laboratories.

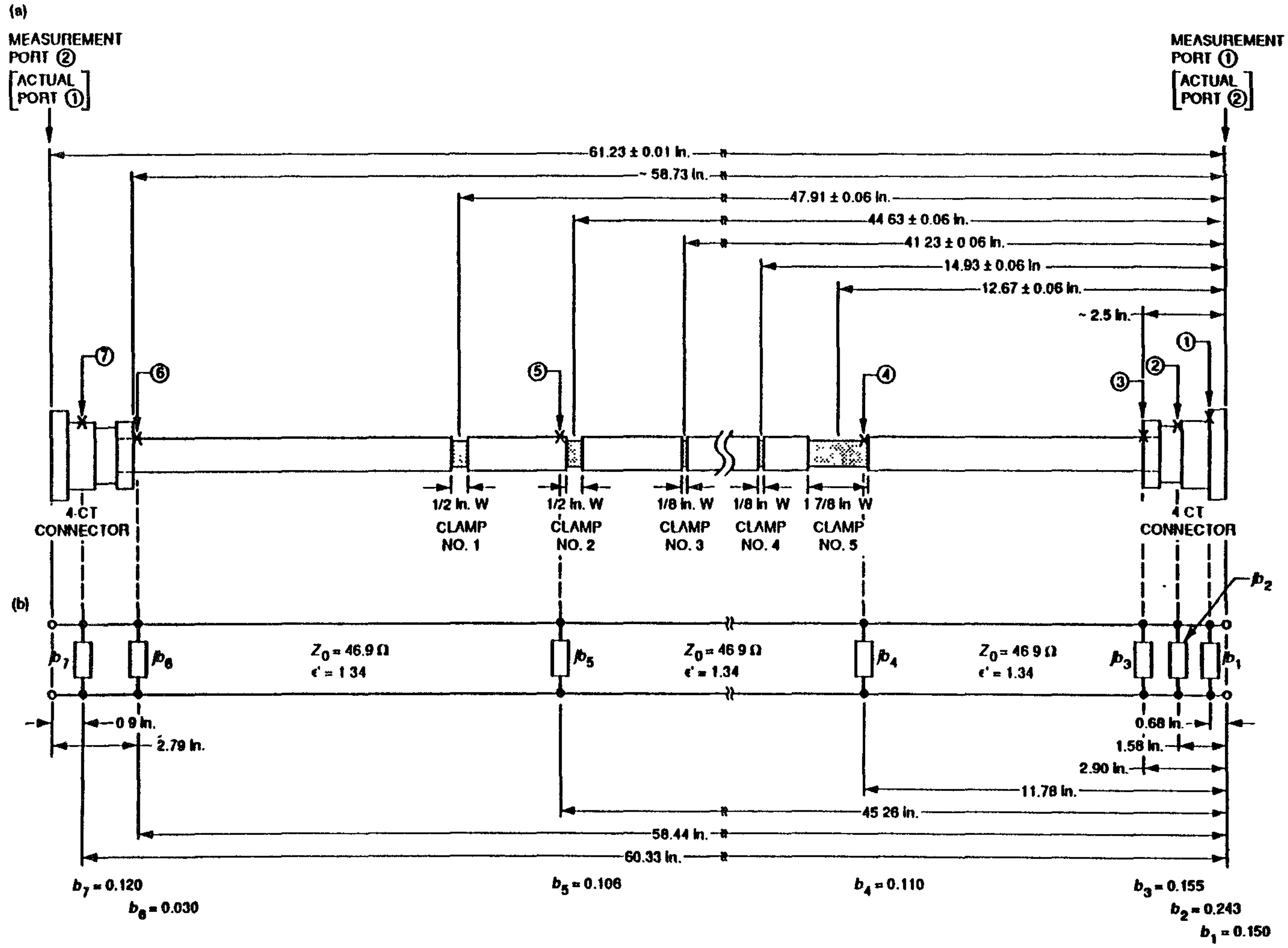

Fig. 3. Model 4: (a) location of discontinuities relative to connectors and cable clamps and (b) equivalent circuit.

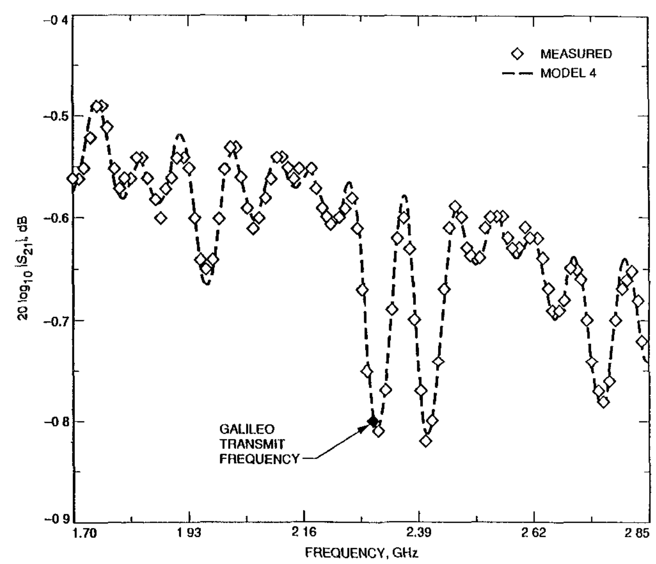

Fig. 4. Comparison of theoretical and measured insertion losses for Model 4, assuming capacitive shunt susceptance values that are constant over the frequency range of interest.

the result of best fitting 15 parameters (seven discontinuities and eight line lengths) by using 101 frequency points for a frequency range of 1.7–2.85 GHz. Line losses between discontinuities for Model 4 were properly accounted for at each frequency. As can be seen in Fig. 3, the Model 4 discontinuity locations correspond very closely to the actual locations of cable clamps, the edges of the Kynar sleeve, and internal discontinuities of the connectors. The locations of these modeled discontinuities are estimated to be within ± 0.5 in. of the actual cable discontinuities.

Good agreement was obtained between theory and experiment for insertion and return loss data, (see Figs. 4–6), as well as for time domain data (see Figs. 7–8). Fig. 9 shows that when all discontinuities except two outer connector discontinuities were removed, the agreement between the model and pre-environmental test data was also excellent. For all of the experimental data that was available, Model 4 was an excellent representation of the Galileo S-band cable.

The sharp edges of the cable clamps and the Kynar sleeves are the probable cause of the discontinuities on the outer diameter of the cable. The cable clamps should be redesigned so that crimping or creasing will not occur when the cable is bent against the clamps. Analyses showed that a 0.02 in. reduction (in the nominal 0.220 in. outer diameter of the Galileo cable) could produce discontinuities of the magnitudes

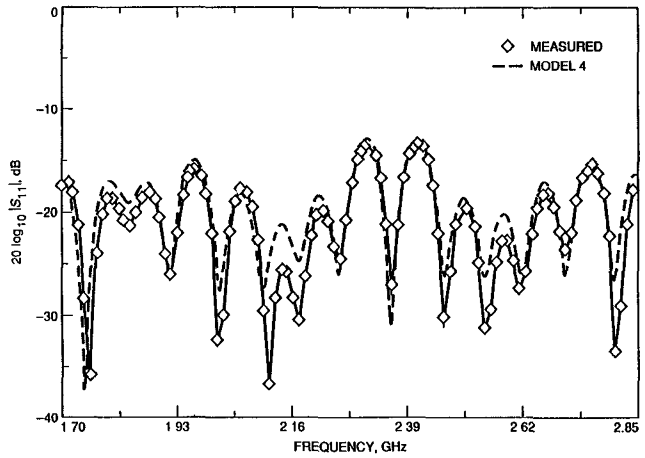

Fig. 5. Comparison of theoretical and measured return losses for Model 4, as seen looking into port 1.

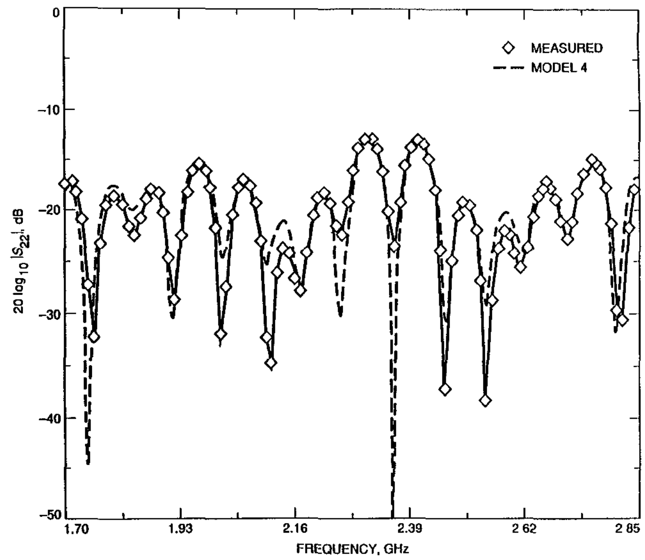

Fig. 6. Comparison of theoretical and measured return losses for Model 4, as seen looking into port 2.

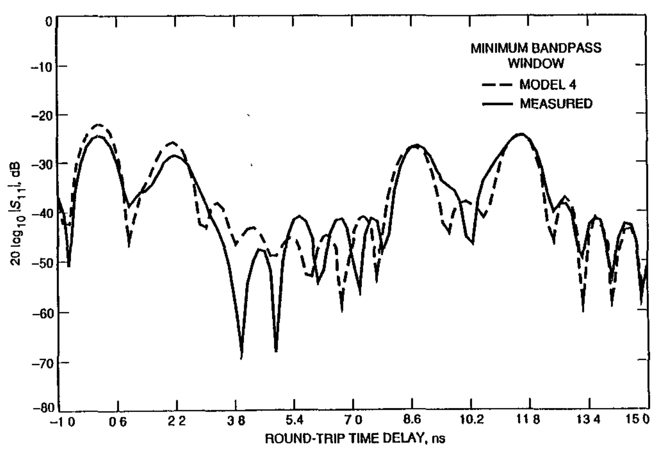

Fig. 7. Comparison of theoretical and measured time domain responses based on S_{11} data for Model 4.

presented in the models studied. For antenna cables that are to be used on spacecraft in the future, the edges of the

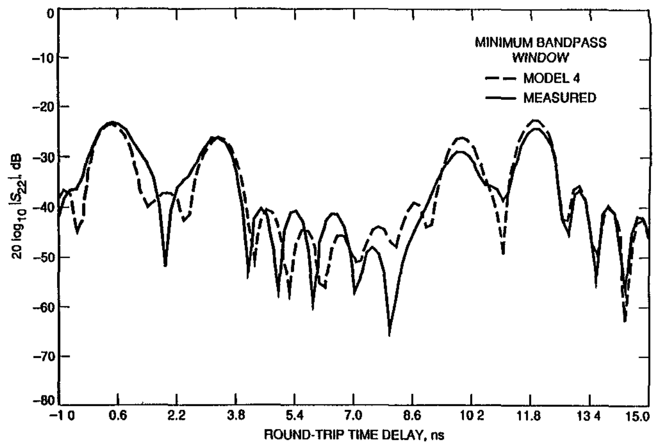

Fig. 8. Comparison of theoretical and measured time domain responses based on S_{22} data for Model 4.

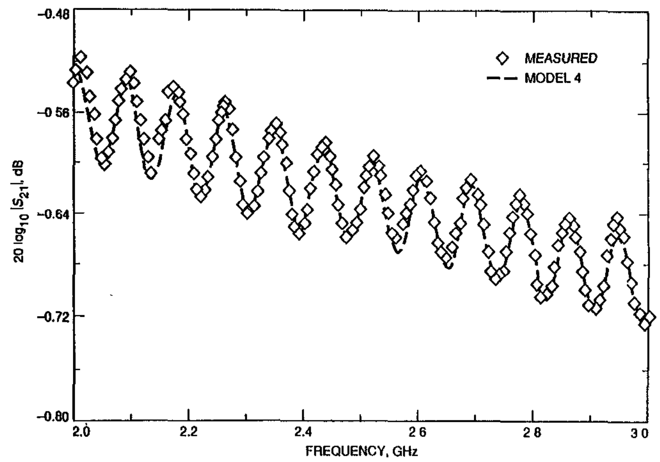

Fig. 9. Comparison of theoretical and measured insertion losses for Model 4 for the pre-environmental cable condition.

currently rigid sleeves should also be redesigned and made flexible.

V. Conclusion

With the aid of the NLSF program, a model has been found that gives excellent agreement between theory and experiment for the Galileo spacecraft S-band antenna cable. The method presented here was demonstrated for a coaxial cable, but the technique can be also be used for the modeling of discontinuities in rectangular and circular waveguides.

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Mr. Otoshi received a NASA Exceptional Service Medal in 1994. He is a member of Tau Beta Pi and Sigma Xi.