Correction of Transmission Line Induced Phase and Amplitude Errors in Reflection and Transmission Measurements

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Abstract— **Measuring the RF, microwave or millimeter wave performance of materials and components often requires a substantial length of transmission line or cables to connect the microwave source/receiver to the test apparatus. Such cables may be subject to environmental variations (e.g. temperature or pressure) that change the overall phase delay and amplitude of signals that travel through said cables. Furthermore, some testing requires physical motion of the cable, which is another source of phase and amplitude error. This paper describes a new correction method, which determines and corrects for phase and amplitude errors in transmission line cables (patent pending). Unlike previous published methods, the present technique does not require any specialized circuitry at the device under test (DUT). Instead it utilizes in-situ reflections that already exist in the measurement apparatus to obtain a reference phase and amplitude signal. The described algorithm combines these reflections with frequency and time-domain signal processing to compensate for erroneous phase and amplitude shifts that occur during a measurement. This paper demonstrates the correction methodology with materials measurements examples. Additionally, this phase and amplitude correction may be applicable for scatter and antenna measurements. It can be applied to either reflection or transmission measurement data.**

I. INTRODUCTION

RF cables or transmission lines are almost always part of a radio frequency (RF) or microwave or millimeter wave measurement apparatus. These transmission lines or cables are used to connect the microwave source/receiver to the test fixture. Cables are therefore subject to environmental variations such as temperature or pressure. These environmental variations will cause changes in the overall phase and amplitude of signals that travel through the cables. In some cases, testing also requires physical motion of the cable(s), which creates another source of phase and amplitude error. When possible, great care is taken to design a test apparatus or methodology to minimize movement of the test cables, so that these position-induced phase errors are also minimized. However, there are measurements, such as those that use scanning sensors or antennas, that necessitate motion so that position-induced phase errors cannot be avoided.

The problem of cable-induced errors has been a concern for many applications. For example, Hahn and Halama [1] were concerned with the phase variation of a long cable in their apparatus. They compensated for this phase variation by terminating their cable with appropriate microwave circuitry. In particular, the circuitry provided a controlled reflection that could be measured with a phase measurement circuit at the source. Subsequent motorized cable stretching was then used to compensate for the measured error. In another example, Roos [2] used a test head to locally mix RF signals at the test location. They found that these signals could experience phase errors even in the intermediate frequency (IF) signal, particularly when that signal was transmitted to a microwave network analyzer over a length of cable that experienced movement. In their method, measurement of a separate phase stable reflection reference and comparison to the device under test was used to compensate for phase errors induced by the cable.

In the author's own work, microwave probes have been utilized as reflectometers for in-situ measurements of microwave materials and components. The measurements have been accomplished on non-trivial geometries in a manufacturing enviornment, thereby requiring robotic integration [3]. An example is shown in the photograph of Figure 1, which pictures a 2-20 GHz spot probe mounted on a robot along with an RF cable integrated into an engineered cable management system. In other cases, measurements may be required over long periods of time where ambient temperatures can change enough to cause errors. An example of this is shown in Figure 2, which shows a focused beam measurement system with a high-temperature oven. Oven measurements necessarily take hours to conduct and the oven itself can be a source of significant temperature drift within even a temperature controlled laboratory environment.

While there are recent technologies that can eliminate the need for a cable connecting a sensor to a microwave source/reciever [4], many cases still require a sizeable distance separating the sensor from the microwave hardware. This is especially true for measurements at frequencies higher than X-band. Therefore, this paper describes a method to determine and correct for phase and amplitude errors that occur in transmission line cables that connect a microwave transmitter / receiver to a measurement device [5]. Unlike the previous procedures to address cable phase errors, the present method does not require any specialized circuitry at the measurement fixture. Instead it utilizes in-situ reflections that already exist in the measurement fixture to obtain a reference signal. Additionally, the described correction method combines these fixture reflections with frequency and time-domain signal processing to compensate for erroneous phase and amplitude shifts that occur during a measurement procedure.

Figure 1 Photograph of robot with microwave spot probe and RF cable that must flex with robot motion.

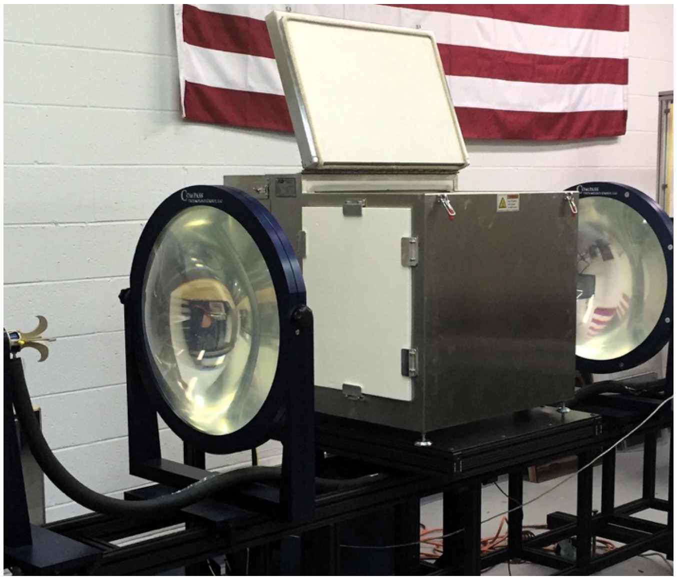

Figure 2 Photograph of high temperature oven in focused beam measurement system, which can cause nearby RF cables to heat up over time.

II. METHOD DESCRIPTION

Transmission line cables are commonly used to connect different microwave components together. In a measurement system, a cable or waveguide is used to connect a microwave source/receiver to a measurement fixture or sensor, as shown in Figure 1 and Figure 2. That measurement fixture interacts with a component, material, or target under test, which is referred to in this paper as a “specimen under test” or SUT. Signals used to excite the measurement fixture and signals received from the measurement fixture are transported to and from the microwave source/receiver via the transmission line or cable. For example, a radar cross-section range measures electromagnetic scatter from a target with a radar connected to an exciting antenna via a coaxial cable or a waveguide. The antenna then is used, often in conjunction with other beam forming elements, to illuminate a target. The reflected energy from that target is received and transported back to the radar system via the connected cable or waveguide. The reflected signals of both the target under test and the calibration targets may be determined with a radar or with a network analyzer. In another example, a materials measurement apparatus may consist of a microwave network analyzer, connected to an antenna or probe by a cable. That antenna or probe is then used to illuminate or excite a material specimen and to receive the reflected energy from that material specimen. The received energy is then transmitted back to the network analyzer via a cable.

Figure 3 shows an example of the signals measured from a material measurement apparatus similar to that shown in Figure 1. In this example, a microwave network analyzer excites the apparatus at a series of frequencies stepped from 2 to 20 GHz. The apparatus includes an approximately 4.5 meter coaxial cable that connects the network analyzer to a near field probe, which in turn illuminates a material specimen. The reflection from that specimen is received by the probe and measured by the network analyzer. The data shown in Figure 3 are an example of what occurs after the reflected signal has been mathematically transformed from frequency domain to time domain. The reflections from the probe are evident as peaks in this time-domain signal. As the data indicate, the round-trip time for the signal to travel from the network analyzer port to the probe is approximately 45 nanoseconds. In this example, there is a second peak evident approximately two nanoseconds after the probe reflection, and this second peak represents the primary reflection from the specimen under test or from a calibration specimen, depending on what is being measured.

An important aspect of the calibration procedure for these data is vector-subtraction of foreground and background signals from the signal of interest. Foreground signals are unwanted reflections that occur before the signal of interest, and background signals are unwanted reflections that occur after the signal of interest. If these foreground and background signals are not properly subtracted, they then impact the desired signal in the frequency domain. In this example the reflection of the measurement fixture (probe antenna) is an unwanted foreground signal. As Figure 3 indicates, reflections from the probe may be immediately adjacent to or even overlap the specimen under test. This vector subtraction is done for both measurement of calibration standards and measurement of the specimen under test. However if the ambient temperature changes, then thermal expansion can cause the length of a cable to change in between calibration and specimen measurement, which imposes an erroneous phase shift that is different for the specimen measurement than it is for the calibration measurement(s). Similarly, if the cable is physically moved or disturbed during the measurement, then that cable displacement can also impose a significant phase or amplitude change that degrades the quality of the background/foreground subtraction.

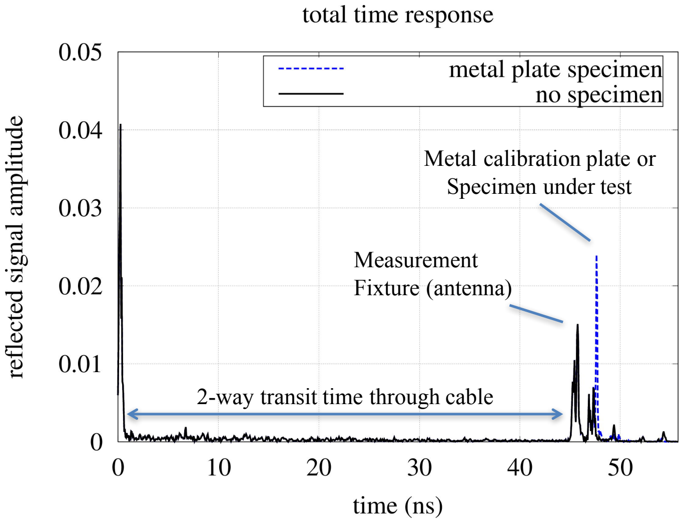

Figure 3 Measured time-domain signal from a probe-based material measurement system.

Figure 4 is a flow chart illustrating the correction method for addressing the errors caused by these cable phase and amplitude changes. The first two steps of this flow chart are partially illustrated in Figure 3. In particular, Figure 3 shows a calibration measurement of a known reference material, a reflective metal plate, as well as a second reference measurement to no specimen (free space). The data shown in Figure 3 are after the received signals have been transformed from frequency domain into time domain via a Fourier transform.

Comparing the time-domain signals with and without a calibration or unknown specimen under test makes it possible to discern the reflections caused by just the measurement fixture. For calibration, the measurement fixture reflections are subtracted from the known reference measurement as well as from subsequent measurements of unknown specimens. However, when environmental or physical changes in the cable cause the measurement fixture reflections to occur at a slightly different time, the unwanted parts of the signal are not properly subtracted. In the frequency domain, this time shift is equivalent to a frequency-dependent phase error that degrades the vector subtraction of the foreground or background (i.e. the probe reflections in this example) from the unknown specimen under test. Thus the second and third steps of the method illustrated in the flow chart of Figure 4 use these time domain signals to determine the exact location of the measurement fixture reflections in time so that they can be monitored during subsequent data collections.

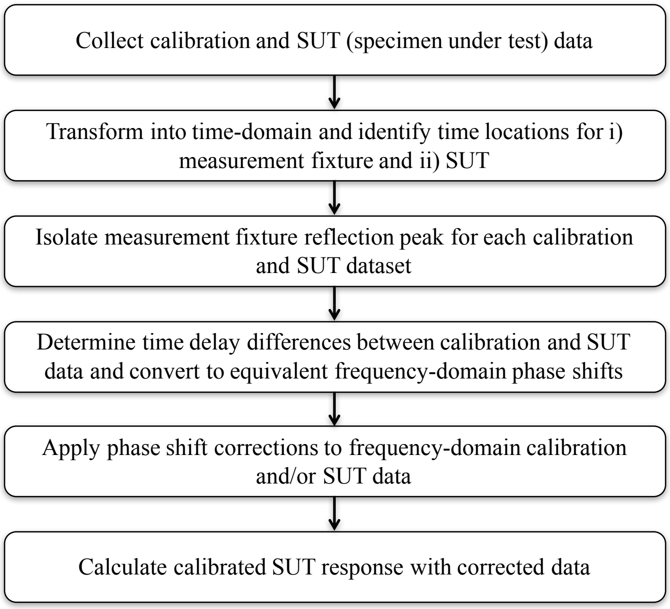

Figure 4 Flow chart of correction method

The fourth step described in Figure 4 determines the time delay / phase error imposed by environmental effects or motion of a cable, and an illustration of the time delay that may occur is shown in Figure 5. Two instances of the reflected signal from a measurement fixture are shown: one before the cable was moved and one after. As these data show, the cable motion imposed a 4.3 picosecond additional time delay between the first measurement and the second. At 2 GHz, this time delay corresponds to an approximately 3 degree phase error while at 18 GHz, the same time delay is approximately equivalent to a 28 degree phase error. Note that identifying this delay can be done by comparing an appropriate time window of the two signals. For example, an automated computer algorithm may be used to subtract the two signals while iteratively shifting one of them in time relative to the other. The minimum subtracted value occurs when the shifted signal exactly overlaps the other signal in time, and this corresponds to the delay. Note that other mathematical methods may also be used to determine this delay between the two signals.

The fifth step of the phase correction method illustrated in Figure 4 then uses this knowledge of the phase error or time delay differences to apply a phase correction. This operation can be done in either time or frequency domain as they are mathematically equivalent. In frequency domain, the phase correction can be applied by multiplying the signal-to-be-corrected, *S*, with the exponential function of radial frequency, ω, times the time delay, *t*, multiplied by the square root of negative one,

$$S^{corrected} = S^{uncorrected} e^{-i\omega t}. \qquad (1)$$

Another example of correcting the measured signals is illustrated in the flow graph of Figure 6. This example differs from Figure 4 in that the phase offsets are determined after the signal from the measurement fixture is transformed back into frequency domain again. In frequency domain the ratio of two measurement fixture signals can be used to determine the phase shift between the two signals. That phase shift, $\theta(f)$ can be fitted to a straight line, which is then used to determine a frequency-domain correction factor. Additionally, it is possible for cable motion to result in a small amplitude error. The mean of the absolute value of the amplitude ratio between the two signals, α can thus be calculated. The signal of interest is corrected by multiplying it in frequency domain by the amplitude, and phase correction factors combined,

$$S^{corrected} = S^{uncorrected}\alpha e^{i\theta}. \tag{2}$$

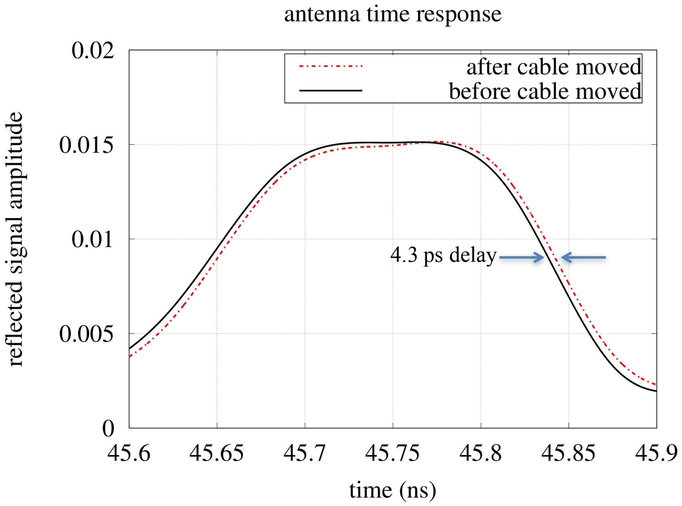

Figure 5 The measured time-domain effect of cable flex on the reflection from the sensor probe.

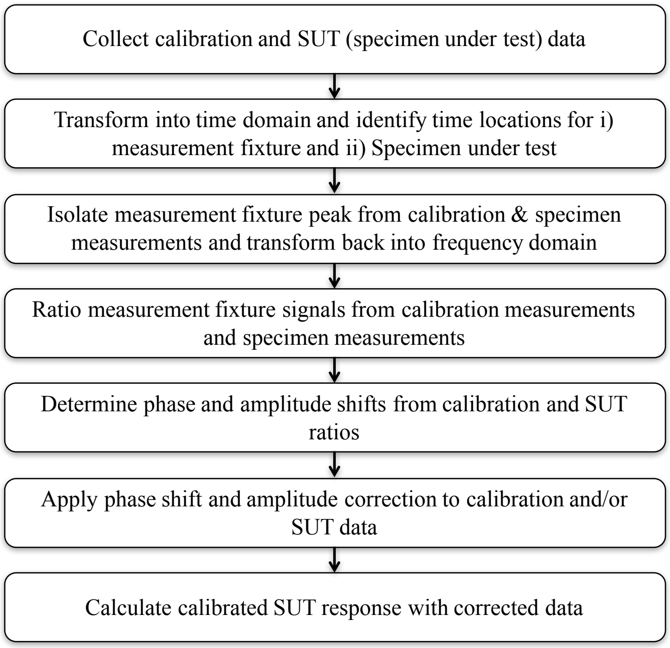

Figure 6 Flow chart of alternate correction method.

Figure 7 shows the result of vector subtractions of the foreground / background from a measurement of a material specimen. The dotted line shows the vector subtraction done without correcting for the extra time delay imposed by the cable motion. This is the traditional calibration procedure applied to measurements of this type. The solid curve shows the same subtraction done after the material specimen measurement was corrected for the 4.3 picosecond phase delay shown in Figure 5. These data show that without the proper phase correction, the measurement fixture reflections may not be fully subtracted thereby increasing the measurement errors. Thus, the phase and amplitude correction method described here significantly improves measurement accuracy by more fully eliminating measurement fixture artifacts.

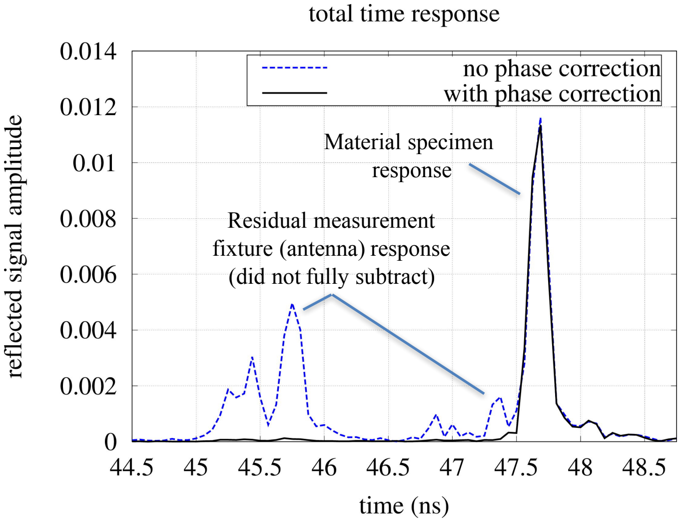

Figure 7 Vector subtraction of ‘empty’ from specimen measurement, with and without correction applied.

The final step of the correction method then applies a calibration calculation to the measured data, which also includes the appropriate phase and amplitude corrections. Figure 8 shows an example of a fully calibrated reflection measurement of an absorber material backed by a conductive sheet. Three different calibrated curves are shown in this figure. All the data shown in this figure were calibrated using a ‘response and isolation’ methodology [6]. The response measurement was of an ideal microwave reflector, in this case a flat metal plate, while the isolation measurement was of no specimen (free space). The calibration procedure first vector-subtracts the isolation measurement from both the response measurement and from the measurement of the specimen under test. When the additional cable correction method is used, the phase and amplitude correction is applied at each vector subtraction step. In other words, the isolation measurement is vector subtracted from the corrected specimen-under-test data, and the isolation measurement is also vector subtracted from the corrected response data. The final calibrated reflectivity, $S^{calibrated}$, of the specimen is then the ratio of the subtracted specimen data to the subtracted response data.

$$S^{calibrated} = \frac{S^{corrected}_{specimen} - S_{isolation}}{S^{corrected}_{response} - S_{isolation}} \tag{3}$$

The thin solid line of Figure 8 shows the calibrated measurement, where care was taken to not move the RF cable between the calibration measurements and the specimen measurement. In this measurement example, a network analyzer was used along with a microwave spot probe that was held in close proximity to the specimen under test. The spot probe illuminated a small area of the specimen, providing a localized measurement of the material reflectivity. The dashed line shows the same specimen measured after the RF cable that connected the network analyzer to the spot probe was moved, but without any phase correction. The dash-dot line shows the specimen measurement after the cable was moved but when a phase and amplitude correction is made by applying the described method. The corrected data after cable movement almost completely overlays the calibrated data for when the cable was not disturbed. As these data show, cable movement can significantly degrade the accuracy of an RF measurement, but the described correction method can almost fully account for these errors.

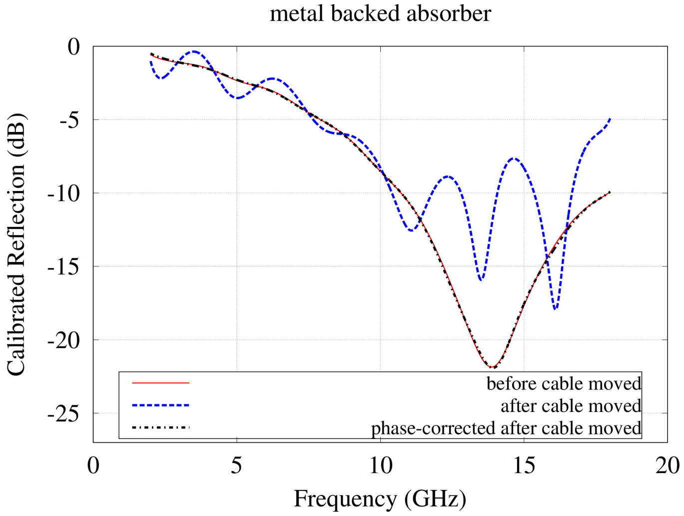
metal backed absorber

Figure 8 Effect of correction method on measured reflection coefficient.

III. APPLICATION TO MULTIPORT MEASUREMENTS

The cable phase and amplitude correction method may also be applied to multi-port measurement fixtures as shown in Figure 9. This drawing shows an example two-port measurement arrangement in which two devices are used to characterize an unknown specimen. For example, in a free space material measurement fixture such as shown in Figure 2, two antennas may be placed on either side of a planar specimen and both reflection and transmission can be collected at the same time. Just as the reflection data may suffer from cable-induced phase errors, so can transmission data. Recall that the disclosed correction method applied to reflection depends on a reference reflection signal from the measurement fixture to establish a phase reference. This reference reflection does not exist in the transmission data. However, if transmission is measured at or close to the same time as the reflection, then the reflection corrections can be used to also correct for the transmission phase errors. In particular, the above-described correction methods determine the two-way phase errors for each port independently. To obtain the transmission phase error between two ports, the one-way phase error of each port (i.e. half of the two-way phase error) may be added. In time domain, this is equivalent to adding the one-way time delays of each port. In the case of transmission, the delay of interest is between the measurement of the specimen and the measurement of no specimen.

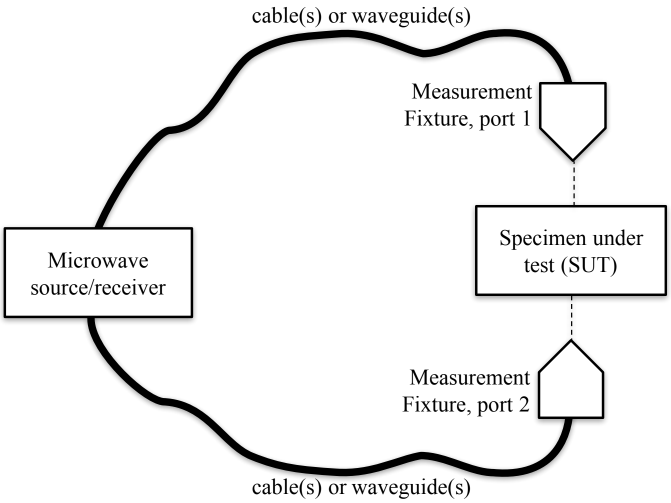

Figure 9 Notional configuration of a 2-port measurement method

An example where the single-port reflection phase errors in each direction are added to correct the two-port transmission is shown in Figure 10. The dashed and dash-dotted lines show transmission phase measured by an apparatus consisting of two microwave probes on either side of a 6.35mm thick acrylic specimen. A calibration measurement was made with no specimen, and then the material specimen was inserted between the probes for subsequent measurements. The data shown are the ratio of the specimen measurement data to the calibration measurement data.

The cables connecting the probes to a network analyzer were physically moved in between the calibration and the specimen measurements, inducing a frequency dependent phase change as seen by the difference between the uncorrected curves. Two measurements were made with the cable twisted in different ways to induce different phase errors. Except for the cable-induced errors, these curves are supposed to overlay since they are measurements of the same specimen. With the phase correction method described above, the single port reflections were used to determine the delay from these cable movements in time-domain. The calibration of the transmission data is then accomplished by dividing the transmission through the specimen under test by the transmission through the same fixture, but with no specimen inserted. The phase correction is applied by multiplying this calibrated transmission signal by the exponential function, $e^{-i\omega t}$.

Applying these phase corrections to the measurement data result in the solid curves also shown in Figure 10. As these results show, this phase correction significantly reduces the phase errors from the cables and the two corrected measurements now almost overlay as they should. Thus the correction methods described here may be applied to both reflection and transmission data in multi-port measurement fixtures.

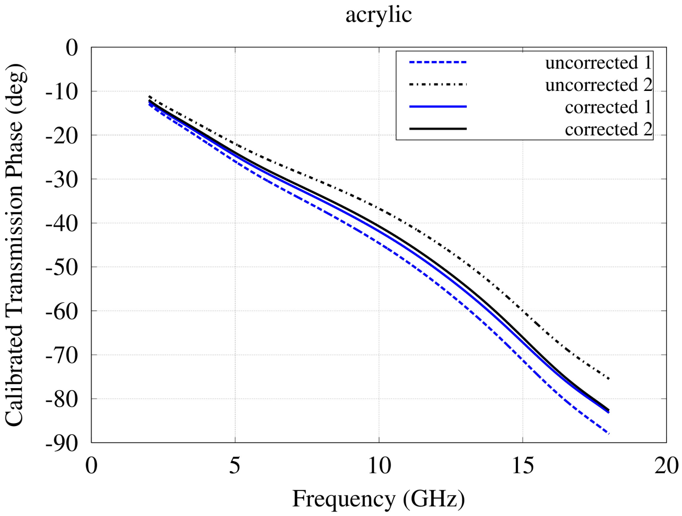

Figure 10 Effect of port 1 and port 2 corrections applied to S21 and S12 (transmission) phase data.

IV. CONCLUSIONS

This paper describes a method for correction of phase and amplitude errors that occur in cables and waveguides connecting microwave source/receiver devices to measurement fixtures. In one example, a method is described that includes using time domain processing to determine the phase shift from the measurement fixture that may occur between calibration measurements and measurements of the specimen under test. In another example a method is described that includes frequency-domain processing of the signals to obtain both phase and amplitude corrections. Measured data are shown to demonstrate how the method works and to validate its ability to correct for phase and amplitude errors. Including these phase and amplitude corrections in the calibration procedure minimizes the errors induced in microwave measurements when the cables or transmission lines experience either temperature changes or physical deflections, among other things.

ACKNOWLEDGEMENT

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