Applying Advanced Methods to Optimize Characterization of *In Situ* RF and Microwave Cables

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Abstract: Stringent system specifications impose tough performance requirements on the RF and microwave cables used in aerospace and defense communication systems. With typical tools, it can be very difficult to perform rigorous testing of the long cables installed in ships and aircraft. This paper presents multiple ways to efficiently and effectively test in situ RF and microwave cables. It also provides useful comparisons for your consideration: different types of solutions; solution cost and complexity versus performance benefits; and measurement range and uncertainty of the various solutions.
RF and Microwave Cables

- Core components in all RF systems. There is no system that does not have cables.
- Even high-quality cables have problems.
- Cables are often the weakest link.
- Common problems:
  - Problems due to bends in the cable
  - Water ingress at junctions
- Therefore cables must be tested.

Cable measurements are required to verify and troubleshoot the electrical performance of RF and microwave transmission systems. Measurements are made on coaxial cables or waveguide systems. During the installation, operation and maintenance of an RF or microwave system, the connecting cables may become damaged or show reduced performance over time. Therefore these cables need to be tested.
Here are three common techniques used today that can be used to measure the insertion loss of a cable or transmission line. The traditional 2-port method, shown on the left, is the configuration to use when both ends of the cable are accessible. This configuration will result in the highest measurement accuracy as a full 2-port calibration can be used to remove all measurement errors associated with adapters and jumper cables required for the test.

The center configuration shows a technique for measuring the insertion loss from only one end of the cable. Often when a long cable is installed into a system, it is difficult to physically connect a network analyzer to both ends without introducing an equally long jumper cable into the test setup. Fortunately, the 1-port cable loss technique will eliminate the need to carry an extra-long, high-quality test cable as part of the equipment requirements for on-site testing. This simple 1-port configuration requires a single connection to one end of the cable and leaving the other end either open or terminated in a short. It is preferred at microwave frequencies to use a shorted termination to eliminate fringing fields found in an open-ended cable which could alter the measured results. In this configuration, the VNA measures the S11 of the cable and calculates the one-way insertion loss from the two-way reflected measurement. This technique is ideal for cables whose insertion loss is less than 30 dB. When the insertion loss is larger than 30 dB, the dynamic range of the test system begins to reduce the accuracy of the measurement.

The Power Sensor method is the configuration for measuring cable loss and requires that both ends of the cable be accessible. Here the RF/microwave signal from the source enters one end of the cable and the attenuated signal is measured at the other end using an average power. While considered better than 1-Port measurements for Long Cables (>20m), this technique is limited by low dynamic range of Power Sensor, risks of external interference (settling time) during measurements and needs a Normalization Calibration before measurements.
The traditional 2-Port method, shown here, is the configuration for measuring cable loss and requires that both ends of the cable be accessible to the VNA.

Here the RF/microwave signal from the VNA is incident upon one end of the cable and the attenuated signal is measured at the other end.

The ratio of the signal amplitude leaving the cable to the signal entering the cable is defined as the cable loss.

This is the most accurate method as it takes advantage of a VNA’s full 2-port error correction ability.
In this configuration, the VNA injects a test signal into the cable and after the signal passes through the cable, it is reflected from the open end (or shorted end) and returns through the cable a second time. Once the reflected measurement is complete, the VNA, using a built-in model for coaxial cable dispersion and knowing that the measured signal contains twice the cable insertion loss can display the cable insertion loss as a function of frequency.

A 1-port cable loss measurement is based on a 1-port return loss measurement. An important factor affecting the accuracy of the cable loss measurement is the difference between return loss and insertion loss of the cable under test. If the cable has excellent return loss (>40 dB), then the uncertainty contribution from the return loss of the cable is minimum. However, if the cable’s return loss is poor, then it has a significant impact on the 1-port cable loss measurement, and the cable return loss becomes the dominant error term in characterization of the insertion loss.

You can enhance the accuracy of the 1-port cable loss measurement by performing a normalization using a load at the end of the cable. Let us look at the two first-order uncertainty terms. (1) The RL uncertainty of the measurement, which you read off the published VNA charts. (2) The cable loss/RL uncertainty, due to the RL of the cable under test. For example, let’s say you have a cable with an average cable loss of 5 dB. A cable loss of 5 dB translates to a 10 dB return loss measurement. If you look on the N9912A uncertainty chart, you will see that for a 10 dB RL measurement, there is ~0.3 dB of error. Now let’s say the cable’s own RL is 20 dB. You have a 20 dB error vector, for a 10 dB measurement. This translates to a 2.5 to 3 dB error. This 2.5 to 3 dB error caused by the cable’s RL is significantly more than the 0.3 dB uncertainty due to the 10 dB RL. If you used data-memory with a 40-dB load, then that 20 dB effectively becomes 40 dB. With a 40 dB S11, you end up with +/- 0.3 dB of error. You add this 0.3 to the original 0.3, for a total of 0.6 dB uncertainty. So one-port cable loss measurements are simple, but the user has to be aware of the decreased measurement accuracy, or use data-memory with a load.
The Power Sensor method is the configuration for measuring cable loss and requires that both ends of the cable be accessible.

Here the RF/microwave signal from the source enters one end of the cable and the attenuated signal is measured at the other end using an average power Power Sensor connected via USB (or USB to LAN Extender).

While considered better than 1-Port measurements for Long Cables (>20m), this technique is limited by low dynamic range of Power Sensor. It is also a broadband measurement, so it requires a clean source, or it is susceptible to errors due to harmonics.
We covered the three common methods to test cable loss in the field: a 2-port VNA measurement, a 1-port VNA measurement, and usage of a power sensor.

Now let's look at some challenging scenarios such as on board ships, on aircrafts, or in submarines, where access is very difficult, and the cables need to be measured in-situ.

Additionally, these are mission-critical system, so accuracy and repeatability of the measurement is of utmost importance.
Let’s look at some of the difficulties of making measurements in the challenging scenarios.

One issue is the long distance between the two cables, which makes it hard to bring the two ports together to where the VNA is located. Many of these cables are part of a larger system that requires tuning, so real time speeds are required, which often is a hassle if a power-sensor based system is used. They need high dynamic range because if you have 200 ft. of RF cable, you will have significant loss, and therefore need a solution with high dynamic range to characterize the loss. Customers using scalar systems would often have to use external amplifiers to increase the dynamic range.

High accuracy is needed because these are mission-critical systems and have tight tolerances. It goes without saying that the measurements need to be repeatable in the harsh environments in which they are performed because they are mission-critical systems.
Today for these challenging environments there are three common solutions: one is a signal generator and power sensors, another is a scalar network analyzer system, and last we will be introducing the new system ERTA, or Extended Range Transmission Analysis.

These will be explored in the next slides.
A signal generator-based system to measure loss is very simple and common. It’s simply a ratio of two power sensor measurement paths, one which includes the DUT, and one which does not. These systems were made popular by the availability of 200 ft. long power sensor/detector cables. These cables carried DC or low-frequency AC signals, so length was not an issue. One power sensor or detector could be carried to the far end, where the end of the RF transmission line cable was located.

These solutions are good solutions, except they are very slow, because of the sensor settling time, and also the dynamic range is limited by the power sensor’s range. Finally the source needs to be clean (not as much of an issue if an expensive microwave source was purchased). The solution has some challenges for the difficult environments of onboard ships, or on subs.
Impact of Source Harmonics
A critical consideration when using sensors or detectors

Harmonic error impact on a power measurement
- Source harmonics : 10 dBc => Error: 0.4 dB
- Source harmonics : 20 dBc => Error: 0.04 dB
- Source harmonics : 30 dBc => Error: 0.004 dB (negligible)

When using a broadband measurement receiver such a power sensor or a scalar detector, it is important to pay attention to source harmonics and their impact on the measurement. Sensors or detectors are inherently broadband devices, that is, they measure all signals, independent of their frequency. Therefore if the source or signal generator has harmonics or other mixing products, those products will be measured by the sensor.

Now in some cases a user may want the "whole power", independent of the frequency, so in that case a power sensor may be fine. But in most cases a clean CW power is desired. In that case, if the signal generator has harmonics, the errors due to it should be included in the measurement uncertainty. The chart here shows potential errors due to source harmonics.
One of the most common methods users in ships, aircraft, or submarines have been testing long cables is using scalar network analyzers. These instruments were widely used due to the availability of long lengths of cables for the detectors. Their benefits compared to a power sensor based system was their speed. They were swept frequency measurements, and very fast. They also had the source integrated into the analyzer, so it simplified the setup. The detectors often had very good match, which minimized mismatch errors, a key component of insertion loss uncertainty.

There were two downsides to these systems: One that they were big and bulky. Users would have to carry a heavy benchtop piece of equipment into small or compact spaces, and these equipment were designed to be used as benchtop products and had relatively high field failure rates. They were good equipment, but were not designed for the harsh environments encountered in the field.

Second issue was that they simply did not have enough dynamic range. So users would often need an external amplifier. The amplifier was another piece of equipment that had to be carried, configured, and broadband microwave amplifiers were very costly.

While these scalar solutions provided accurate measurements, they were not ideal solutions.

Let’s now look at a new solution called “Extended Range Transmission Analysis” or ERTA, which is based on the use of two handheld analyzers.
In general a spectrum analyzer is used to characterize unknown signals, but when paired with a built-in tracking generator it can measure the scalar transfer of some device under test. These measurements typically proceed faster than general SA frequency scans, as the receiver hops along in lockstep with the source energy, never just scanning empty space. The measured result is similar to a scalar S21, and trace normalization can be used to null out the impact of connecting cables. **Extended Range Transmission Analysis** enhances this standard SA capability by putting two FieldFox units to work, one acting as Source and the other as Receiver.
The ERTA application is a spectrum analyzer that knows how to synchronize with a partner unit for tracking measurements. The receiver unit acts as master measuring the output of a device under test while the Source unit responds as slave supplying signal at the input. The two instruments can be separated by hundreds of meters, allowing solutions for unique use cases such as long cable characterization.

With the proper setup (power splitter), the Source unit uses its own SA receiver to measure the reference signal, thus yielding a true B/R ratio measurement. Along with new dual cable corrections capability, this eliminates the need for static trace normalization, because the reference trace is updated on every sweep. Since each SA Receiver stays accurate with InstAlign, the resulting Scalar S21 Transmission ratio can be trusted even if the units are operating at different temperatures.

Handshake signal connections: The trigger/ref OUT port of each unit needs to be connected to the trigger/ref IN port of the other unit. The handshake signals facilitate the essential synchronous measurement stepping to each tune position.

LAN communication signals: The units can either be connected directly to each other with a crossover cable, or they can be together on a network thru a switch or router. The LAN allows for SCPI communication between the units to facilitate a master/slave style partnership.

This configuration is also capable of measuring transmission paths which contain a frequency conversion element such as a frequency downconverter or upconverter.
ERTA’s connection wizard guides the user through the setup process, to ensure a valid connection.

After guiding the user through connection the LAN and trigger cables, it verifies that each of these cables has been correctly configured. If not, it will indicate an x on the screen.

This provides assurance to the user that their setup is correct.
FieldFox’s ERTA Measurement Wizard guides the user through measuring of jumper cables on the source side and receiver side, or input and output sides, if such cables are part of the system.

The loss or S21 magnitude of the cable is measured using the underlying VNA which is part of FieldFox. The calibration that is used is the built-in factory Cal or CalReady, which is an accurate calibration traceable to NIST, done at the test ports.

This S21 or cable loss measurement is very accurate and is used in the measurement.

If users want to use a different method to characterize the cable, or want to upload an insertion loss measured on a different analyzer, the ERTA GUI allows for that.
The ERTA GUI allows the user to examine the input power, output power, or Gain (B/R).

In most instances, the user is interested in measuring insertion loss or gain (B/R). But during the initial setup, it is useful to observe the input power or output power directly.

It is also useful when testing converters, as will be examined later, as the input and output frequencies differ.

The annotation on the left side of the screen indicates the measurement (r, B, and B/r = G).
RF / DUT connections: The preferred setup takes the Source partner signal (port 1) thru a power splitter, returning ½ the power back (port 2) for a reference measurement. The other ½ power is routed thru a connection cable to the DUT. At the output of the DUT a second connection cable brings the transmitted signal back to the Receiver partner (port 2). The preferred setup allows for accurate ratio measurements with specifications. A simplified setup could omit the power splitter, and just route the Source partner’s signal thru the DUT and on to the Receiver partner’s SA input. The simplified setup would just show nominal transmission response without ratio and without specs.
An advantage of ERTA is that it uses the spectrum analyzer as the receiver, it has very high dynamic range, which allows it to be used to measure very lossy cables.

If you have a short run of a cable, let’s say 10 feet, dynamic range is not as critical of an issue, as perhaps you have 5-7 dB loss. But when you have long lengths of cable runs, let’s say 200 feet, then your loss at microwave frequencies can easily run into the 50+ dB range, even 70 or 80 dB. In that case, you need test equipment that can measure even better than that. And that’s where ERTA comes into play.

Some sample dynamic range values for a FieldFox based ERTA system are shown here. For a 50 GHz system, you can measure up to 88 dB of loss. That’s quite an astounding dynamic range for a portable solution.

The plot on the right shows a comparison of a filter measurement using ERTA, compared to a benchtop VNA, and you can see how good ERTA is able to make the measurement.
Maximize Measurable Attenuation by Locking to GPS

- GPS satellites can be used to increase frequency accuracy.
- Sample specifications:

<table>
<thead>
<tr>
<th></th>
<th>Without GPS</th>
<th>With GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency accuracy</td>
<td>± 0.7 ppm</td>
<td>± 0.01 ppm</td>
</tr>
<tr>
<td>ERTA required minimum RBW</td>
<td>3 kHz</td>
<td>300 Hz</td>
</tr>
<tr>
<td>Maximum measurable loss at 10 GHz</td>
<td>83 dB</td>
<td>103 dB</td>
</tr>
</tbody>
</table>

- Better frequency accuracy allows the use of a narrower RBW, which in turn results in a lower noise floor.
- If the GPS signal is not present at all times (in a submarine for example), the GPS hold-over mode can be used.

Locking the analyzers’ frequency references to GPS allows for greater frequency accuracy of the FieldFoxes and use of a narrower RBW, which in turn results in a lower DANL, and hence a wider measurement range. When the GPS signals cannot be present at all times, the GPS hold-over mode can be used.
Here are we looking at the impact of different RBWs on the ERTA measurement. Measurement example: 90 dB of attenuation with a 60 MHz bandpass filter showing measurement optimization through varying resolution bandwidths after a GPS synchronization. When measuring very high loss devices with ERTA, too wide a RBW will cause errors due to high trace noise and too narrow will cause amplitude degradation due to the two FieldFoxes IF filters no longer being aligned. Note that the sweep time increases significantly as the RBW narrows, requiring longer wait times before measurement data displays.
This slide summarize the features needed to maximize dynamic range with ERTA on the receiver side, or the receiver analyzer.

The RBW can be narrowed which results in a lower noise floor. The attenuation can be reduced to zero. And also the internal preamp can be applied for an additional 15 to 20 dB of dynamic range.

Lastly as discussed, the units can be locked to GPS to allow for the use of a narrower RBW.
From the source perspective, an external preamplifier can help increase the net dynamic range. This preamp can be powered off either FieldFox’s variable voltage source or USB (such as the Keysight U7227C), can be added to the source side. Even though the U7227 is a preamp, its output can achieve ~+13 or +14 dBm, about +10 higher than FieldFox’s source output. The U7227C is much more convenient than a benchtop-AC-powered amplifier.

Even though the U7227 is a preamp, its output can achieve ~+13 or +14 dBm, about +10 higher than FieldFox’s source output. The U7227C is much more convenient than a benchtop-AC-powered amplifier, which is what many users are using today.
This slide is not specific to ERTA, but just shows general SA improvements with the use of the Keysight USB preamp. But since ERTA is an SA based measurement, it will also see the same improvements.

Here we are unable to see a -145 dBm signal with the FieldFox’s SA mode, even though the internal preamp is on, and attenuation is set to zero. Once we add the external preamp, we can easily see the signal.

So the preamp can be used to increase dynamic range or sensitivity.
Since the SA is used as the receiver, with a FieldFox configuration, you benefit from InstAlign. InstAlign provides excellent amplitude accuracy.

Also, since the SA is tuned only to the frequency of interest, all harmonics or out-of-bound signals are not measured, resulting in a clean measurement.

Furthermore, the high dynamic range (low noise floor) contributes to overall accuracy. Even if the dynamic range is not needed, it is useful, as it results in a better S/N ratio, reducing overall noise.
ERTA adds offset tracking capability to the source. Source offset tracking allows the DUT to contain a frequency translation device, like a mixer or converter, common components in RF subsystems.

Source tracking offset provides for a mathematical offset between the Source Freq and Receiver Freq at every tune position if the Source is set to Tracking mode.

- **TrackingOffset OFF (default)** \[SourceFreq = ReceiverFreq\]
- **TrackingOffset ON, and Reversal OFF:** \[SourceFreq = TrackingOffset + ReceiverFreq\]
- **TrackingOffset ON, and Reversal ON:** \[SourceFreq = TrackingOffset - ReceiverFreq\]

The spectrum analyzer Amplitude Corrections menu allows for two independent cable responses. The corrections are now called out as either SourceSide or ReceiverSide, to represent cabling on either side of the Device Under Test (DUT). The primary reason for this enhancement is to properly compensate during Offset Tracking measurements, where mapping to unique frequency ranges is necessary depending on the side (source or receiver); however, it is equally valid to characterize two independent cables when Offset Tracking is not enabled. Both corrections are applied on the master FieldFox where final trace processing is performed. Cable Corrections can be setup manually, but there is also a Wizard available under the Cal menu to simplify the setup process.
ERTA is a system that uses two sources. It is useful for measuring a wide range of devices with high dynamic range, and long lengths of cables. It is also very accurate, and simple to use in that no calibration is needed.
This slide shows a comparison of the different methods we have discussed for insertion loss testing.

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Maximum measurable loss</th>
<th>Cable constraints</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Port VNA Transmission, S21 Measures Mag and Phase over frequency sweep</td>
<td>60 to 120 dB depending on the VNA's dynamic range</td>
<td>Two ends of cable must be close enough to perform calibration/measurement</td>
<td>Extremely accurate ±0.1 to ±0.3 dB S21 uncertainty data provided by manufacturer</td>
</tr>
<tr>
<td>Reflection measurement or S11 S11/2 = one-way insertion loss</td>
<td>15 to 20 dB Limited by return loss (RL) measurement range and cable's own return loss</td>
<td>One end of cable needs to be open</td>
<td>±2.5 to ±3 dB with basic measurement ±0.5 dB to ±1 dB with extra step of adding load to the end of cable, and removing effect of load</td>
</tr>
<tr>
<td>Measure loss as a ratio of two power sensor measurements</td>
<td>Limited by power sensor's dynamic range (60-70 dB) None, length of USB cable on sensor, less limitations with LAN sensor</td>
<td>Slow measurement due to sensor settling time</td>
<td>Accurate method, though susceptible to source harmonics</td>
</tr>
<tr>
<td>ERTA – One FieldFox is Source, other FieldFox is Receiver</td>
<td>100+ dB 200 ft. + Cable installed with access to other end of cable</td>
<td>No Warm-up No Calibration req'd (Normalization only) ≈3 to ≈10 faster than Power Sensor Loss measurement ± 0.6 dB</td>
<td></td>
</tr>
</tbody>
</table>
ERTA Summary

- Insertion loss measured on cables in situ with test ports far apart
- InstAlign + Power splitter means NO user calibration, just connect analyzers on each end of DUT and measure
  - Ratio’d measurement eliminates drift
- Exceptional accuracy and dynamic range
  - Most accurate due to SA InstAlign
  - SA's selectivity rejects out-of-band signals
  - SA's dynamic range better than current systems
- Fast wide-frequency range sweeps for tuning DUT
- Performance exceeds current solutions, and ERTA solution adopted by U.S. DOD

To summarize…

ERTA is a system designed to measure the insertion loss of in-situ cables over long distances.

ERTA requires no open, short, load type calibration, simplifying the measurement setup for the user.

It is extremely accurate, taking advantage of FieldFox’s InstAlign capability, and the ratioed measurement between source and receiver, which eliminates any errors due to drift.

It is a fast measurement system, since it is a spectrum analyzer measurement. It is fast enough to be used for real-time tuning.

And lastly, ERTA has been adopted by various departments in the U.S. Department of Defense. ERTA measurements have been compared to previous measurements, and the results have agreed with previous established measurements.
The FieldFox microwave analyzer is a combination cable/antenna test set, 2-port VNA, spectrum analyzer, power meter, independent source and GPS receiver. It is particularly designed for aerospace and defense communication system field test.

Here are a few key features that make FieldFox the ideal tool for field test:

1. VNA, SA, source and power meter in one package
2. No warm up for spectrum analyzer measurements, instAlign technology of FieldFox allows the spectrum analyzer to measure spectrum amplitude as accurate as 0.5 dB, approaching average power sensor accuracy without warm up.
3. The FieldFox signal source can be set independently, which is ideal for measuring frequency converters.
4. ERTA can be used to measure loss of lengthy cables in-situ.
5. Real-time spectrum analyzer for interference analysis.

It is compliant with MIL standards for use in tough environments. It is type tested to use in explosive environments, and it is also type tested for IP53, dust and splash proof.

FieldFox is battery powered and can continuously operate for 3.5 hrs.
References

- **FieldFox Handheld Analyzers 4/6.5/9/14/18/26.5/32/44/50 GHz - Data Sheet** Provides specifications for ERTA.

- **Techniques for Precise Cable and Antenna Measurements in the Field - Application Note** This app note introduces measurement and calibration techniques for cable and antenna testing using FieldFox handheld analyzers.

- **Techniques for Advanced Cable Testing - Application Note** Covers advanced measurement techniques and examples for measuring and troubleshooting transmission lines installed in a system.

- **Scalar Network Analysis with U2000 Series USB Power Sensors - Application Note** The purpose of this application note is to explain how to make accurate scalar network analysis using USB power sensors.
Questions?
Detailed ERTA Diagram

**FieldFox #1** is the source and the reference receiver.

**FieldFox #2** controls all settings, including FieldFox #1's frequency and power. Jumper cable corrections are saved on FieldFox #2. Measurements are viewed on FieldFox #2.

Source

Reference Input

Input Jumper Cable

Output Jumper Cable

Cable or Device Under Test

Test Input

LAN connection between FMS and FRR

FMS Trigger Out to FRR Trigger In

FRR Trigger Out to FMS Trigger In

Source and Reference Receiver (FieldFox #1)

Measurement Receiver (FieldFox #2)