Guide to RF Coaxial Connectors and Cables

Given that typical RF systems are comprised of any number of items, e.g. RF generators, amplifiers, attenuators, power meters, couplers, antennas, etc., it is not uncommon that a great deal of thought is given to these "high end" devices while mundane items such as connectors and cables are often treated as an afterthought. With a wide variety of coaxial connectors and cables available for use in the RF and Microwave spectrum not giving these essential components too much thought is a misstep and can result in undesirable system degradation.

RF coaxial connectors provide vital RF links in communications, broadcast, EMC testing, commercial and military, as well as test and measurement fields. In this guide, you will learn about the different types of RF Coaxial Connectors and Cables and the various uses for each. Guidance and insight will be provided to assist in choosing connectors best suited to accommodate your specific applications.

1.0 RF Coaxial Connectors

The vast array of RF connectors available can be overwhelming, but they are all characterized by just a few key parameters. The most obvious characteristic of a connector is its physical size.
Other considerations include power handling and frequency range capabilities. To ensure maximum power transfer, the characteristic impedance of the connector should match the source and load. All of these characteristics, along with connector durability and cost, must be considered for each application.

The most commonly found connector types in RF applications are available in both male and female configurations, standard and precision grades, high frequency and in some cases high power versions.

1.1 BNC

The BNC connector is perhaps one of the most widely used connectors in the test and measurement field. It was developed by Bell Labs in the early 1950s and is typically used for low power interconnections on RF test equipment such as audio and signal generators, oscilloscopes and amplifiers. The inexpensive BNC utilizes a bayonet retention collar to provide quick mate/de-mate action and also serves to prevent accidental disconnection. The BNC connector is typically designed to provide a characteristic impedance of 50 or 75 ohms, depending on the application. BNC connectors are generally rated for use in the DC – 4 GHz frequency range; however, they are rarely used above 500 MHz. While they are capable of handling 80 – 100 Watts average power up to 1 GHz, they typically do not have a maximum power rating. They do however carry a maximum voltage rating of about 500 V.

1.2 TNC

The TNC connector is merely a threaded-version of a BNC connector. It provides a more secure connection and thus reduces vibration issues that can be found with the BNC. The TNC will operate at higher frequencies than the BNC and there are also high power TNC versions available.

1.3 SMA

The Sub-miniature Type A connector was developed in the 1960s and has proven to be a very popular choice in low power, high frequency applications. It was originally intended for use on 141 type semi-rigid coaxial cable, where the center conductor served as the center pin. Its use was later expanded to flexible cables with soldered on center pins. It consists of an inner contact ring and a hexagonal clamping nut attached via a snap ring. Special wrenches are used to achieve the correct torque; typically 5 lb-inches. There are different versions available such as high frequency, self-locking and precision. Commonly used as interconnects on RF boards, microwave filters, and attenuators, the SMA will operate up to 18 GHz. Precision versions extend the upper frequency limit to 26.5 GHz. Although the SMA will mate to the 2.92mm/'K', 3.5mm, and APC-3.5 connectors, it is not recommended as slight dimensional differences may result in connector damage.

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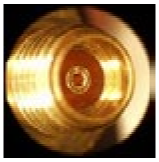
1.4 3.5 mm



The 3.5mm connector is a precision connector primarily developed at Hewlett Packard (now Keysight Technologies). It is similar in design to the SMA but employs an air dielectric for higher performance.
These connectors perform well to 34 GHz, but typically are used to 26.5 GHz. Since the 3.5mm is a precision connector, it is more expensive than similar designs and is thus often found in calibration kits and metrology applications as opposed to common test and production applications.

1.5 2.4 mm

Developed in the mid 1980s by Hewlett Packard (now Keysight Technologies), this 50 GHz connector employs a 4.7mm outer conductor arranged around a 2.4mm center conductor. The 2.4mm is available in three grades; general purpose, instrument and metrology. Since these connectors are not directly compatible with the SMA family, precision adapters are required to mate a 2.4mm connector to an SMA.

1.6 2.92 mm/K Type

This connector was designed and developed by Wiltron (now Anritsu Corporation). Performance with this connector is comparable to the 2.4mm, although the maximum frequency is limited to 40 GHz.
The “K type” designator is derived from its ability to cover all the K-band frequencies.

1.7 N Type

This is one of the most common RF connectors in use around the world today. This high-performance connector was designed by Bell Labs in the 1940s with a threaded coupling interface and internal gasket to keep out the elements. The N connector is rugged, relatively inexpensive and the standard version is capable of mode-free operation to 11 GHz. Precision versions push the upper frequency limit to 18 GHz. Commonly found on instruments such as amplifiers, directional couplers, power meters, and coaxial attenuators, this threaded, durable connector provides a very secure connection. There are both 50 and 75 ohm versions available; the latter commonly used in the CATV industry.

1.8 C Type

The C connector was designed by Amphenol to handle high power applications as well as provide quick mate/de-mate action. It uses a dual-stud bayonet retention collar similar in design to the BNC.
The popularity of the C connector has diminished over the years but is still available. The 7-16 DIN has been used as a replacement in many cases due to its similar frequency and power capabilities. There are 75 ohm versions available as well as an “SC” version which incorporates a threaded collar for a more secure connection.

1.9 7-16 DIN

This is a more recent connector in the United States, compared to the other connectors previously mentioned. The 7-16 DIN was developed by the Deutsches Institut fur Normung, (translation: the German National Standards Organization); hence the “DIN” designation. The numerical part of its name refers to the size of the inner and outer conductors; “7” for the inner conductor OD in mm, and “16” for the outer conductor ID in millimeters. The 7-16 uses an M29 x 1.5 threaded coupling nut.
The 7-16 DIN connector was designed with low inter-modulation in mind for communications applications. Other common applications include antennas, base station connections, RF cables, SATCOM and lightning protection systems.

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1.10 EIA Series

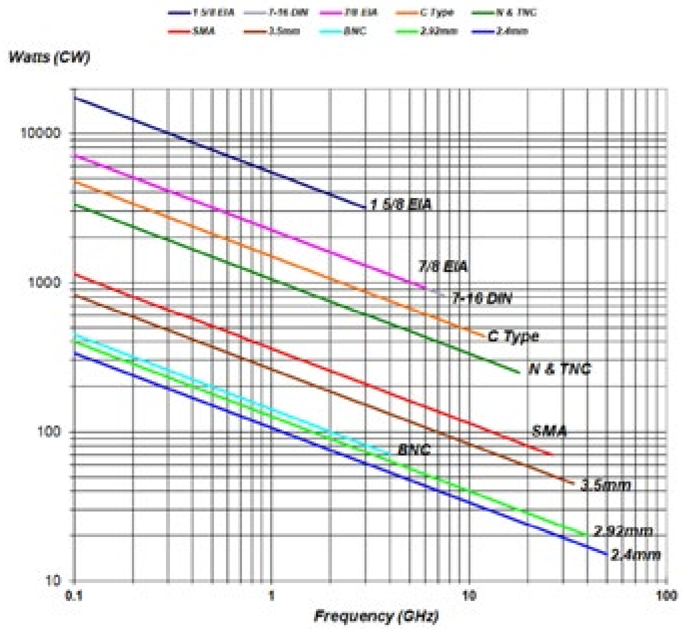
The EIA series of coaxial connectors are available in EIA 7/8", EIA 1 5/8", EIA 3 1/8", EIA 4 1/2" and EIA 6 1/8" versions, all of which are suitable for RF applications. Designed to support cables with foam or air-dielectric, they consist of a main body, mounting flange with various bolt circles, and typically have interchangeable/removable center conductor "bullets". Due to the flexibility of their design, EIA connectors are often not identified as male or female, as the connector can typically be configured as either. EIA connectors can be found in high power applications on directional couplers, coaxial cables, power amplifier outputs, and interconnects on communication towers and antennas. The most common sizes found in general test and measurement applications are the 1 5/8 and 7/8 EIA. There are a variety of adapters available to adapt the EIA series to some of the larger RF connectors such as the 7-16 and N type.

1.11 Making the Right Selection

Now that you have a better understanding of the most popular RF coaxial connector types, let's consider the thought process that should be applied to make intelligent connector choices.

It is important to remember that the specific application will determine the frequency range and power handling requirements of the connector. The chart below is a reference to use when selecting the proper connector type. The chart provides general guidance on power handling of coaxial connector types under the conditions of matched source/load impedance, in a controlled laboratory environment, with connectors of common construction and materials.

Connector Power Handling



This chart should only be used as a reference. Individual connector manufacture's power ratings may differ from these general ratings. Be sure to consult specific manufacturer specifications prior to use.

Connector power handling can vary greatly depending on connector construction, ambient and equipment temperature, and reflected power. The continuous CW power rating of a connector is primarily based on temperature rise due to dissipated power, which results from a combination of I2R losses and dielectric losses. Consequently, heat management becomes the primary factor in power rating. These aspects are discussed in more detail below.

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1.12 Connector Construction and Materials

Materials used in the connector affect power handling capability, with the dielectric material having the greatest effect. Most connectors today use one of several fluoropolymers to capture and support the center conductor of the connector, with polytetrafluoroethylene (PTFE) being the most widely used. Air dielectric connectors such as precision 2.4, 2.9, or 3.5mm connectors may avoid PTFE altogether, and use a higher-temperature material (e.g. Ultem 1000). In other cases, high power connectors may use thermally conductive dielectrics to provide better cooling of the center conductor than PTFE can offer.

The other material of interest is the plating on the center conductor. High temperatures can cause rapid oxidation of the contact materials, increasing resistance and I2R losses. This increased power dissipation drives the temperature even higher, into an eventual run-away condition. Unfortunately, this behavior is not nearly as easily characterized as the dielectric heating, as it is very dependent on the environmental conditions (eg. lab vs. marine) and often proprietary plating materials and thicknesses. However, the more easily characterized dielectric material limitations are the more typical short-term failure mode and power limit.

1.13 Temperature

The temperature of a connector will be influenced by both the ambient air temperature, as well as the temperature of the connected device. Heat exchange through conduction with the mating connector/device will typically have a greater effect than ambient temperature. The objective is to ensure that the internal connector temperature does not exceed the temperature ratings of the internal components, which is primarily limited by the dielectric material temperature rating. Power handling will de-rate from full rated power at the rating temperature, decreasing to zero power at the maximum allowable temperature of the connector materials. Be sure to consult the connector manufacturer for their temperature derating curve.

1.14 Reflected Power

When operating into a mismatched load, some of the incident power will be reflected back to the source. The combination of incident and reflected power traveling on the same cable causes standing waves to form. The measurement of these standing waves is the Voltage Standing Wave Ratio (VSWR). These standing waves result in current peaks and nulls along the cable at quarter wavelength intervals. Higher current translates to higher power, and thus greater heat. The locations along the cable where the peaks of the standing wave occur will be subjected to increased localized heating, resulting in alternating higher and lower temperature regions occurring along the cable. To account for the localized heating due to peak standing wave power, use the following derating calculation:

This is shown graphically here:

$$\frac{1}{\left(1 + \left(\frac{VSWR - 1}{VSWR + 1}\right)\right)^{2}}$$

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1.14 Reflected Power

At lower frequencies, where wavelengths are long and current peaks are broad and well-separated from the adjacent current nulls, using peak standing wave power is good practice.
However, applying the same rule to smaller connectors used at high frequencies may result in impractically conservative power ratings. Due to the short wavelengths at high frequencies, the localized hot and cold areas are small and in close proximity, thus encouraging heat transfer between these regions, reducing the peak temperatures. This thermal averaging reduces the peak temperatures, and as frequencies increase, the VSWR derating begins to approach the average standing wave power, defined as:

$$\frac{1}{1 + \frac{VSWR - 1}{VSWR + 1}}$$

These two derating curves are shown here:

This thermal averaging effect may sometimes allow a more aggressive power rating at higher frequencies, somewhere between the peak standing wave power derating, and the average standing wave power derating. If choosing to do this, consult with the connector manufactures for guidance.

1.15 Pulsed Operation

When operating with pulsed signals, in addition to the aspects previously mentioned, there are several additional factors to consider.

Connectors can handle pulse power levels that are greater than their continuous CW power rating. This is due to the pulse off time, when no heating occurs. This allows the connector to cool during this time, and thus experience thermal averaging over a full waveform cycle. However, the average power over a full cycle of the waveform must not exceed the CW power rating of the connector. The average power is calculated as follows:

$$AveragePower = PulsePower * \frac{DutyCycle}{100}$$

In pulsed applications where the average power approaches the continuous CW power rating of the connector, consult the connector manufacture for additional guidance.

Voltage breakdown must also be considered when operating at very high-power levels.
Operating with very high pulse power levels with very short duty cycles may result in an acceptable average power level. However, the high voltage during the pulse may exceed the breakdown voltage of the dielectric material. This could result in arcing between the center conductor and shield/ground, with subsequent damaged and burned components. Note that voltage breakdown will occur at a lower level in a coaxial configuration than the breakdown level would be in a simple non-coaxial gap configuration of the same distance. Breakdown voltage levels in a coaxial configuration can be calculated to determine connector suitability for an application.

Dielectric material will have a higher breakdown voltage than air. However, when modeling peak voltage limits, good practice dictates using the air breakdown value rather than the higher dielectric material breakdown voltage, as it is likely an air gap will exist somewhere along the RF chain.

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2.0 Connector Mating and Care

Connectors are crucial components in the RF chain and are instrumental in achieving proper performance in the system. As these components incorporate mechanical action, as well as carrying RF, care needs to be taken in use. A damaged connector, if mated, may propagate damage to the mated connector. As connectors can be costly, taking precautions and using care is well-advised.

2.1 Connector Mating

Ensure connectors to be mated are physically compatible and are of the same impedance rating. Be sure to inspect connectors before mating, which may require the aid of a microscope or magnifying glass for sufficient detail. Look for metal particles, fibers, dust, and other contaminants. Check for centered, straight, and undamaged center pin on male connectors, and verify that female jacks are centered, open, and undistorted. Look for body distortion or dents. Depending on jack construction, verify any contacts or spring fingers are in place and undamaged.

Prior to mating, clean both connectors. This is especially important on precision connectors used at higher frequencies, where measurements can be easily affected by contaminants. Clean, dry air, such as canned air, can be used to blow out connectors. Blow across the face of the connector to pull debris out, as blowing directly into the connector may lodge debris more firmly. A small amount of isopropyl alcohol on a lint-free swab can also be used to clean connectors, however, avoid excessive solvent to minimize wicking of solvent into the connector. Air-dielectric connectors are fragile, and if mechanical cleaning of the internal contacts is needed, it must be done with great care. Clean internal and external threads, and check for any burrs or roughness that would interfere with smooth thread engagement.

When mating connectors, carefully align the center axis of both connectors and push straight together as far as possible. While keeping the connector bodies stationary, turn the connector nut by hand to thread onto the mated connector. Never allow the connector bodies to rotate, as this will cause unwanted and unnecessary wear, which may cause permanent damage to one or both connectors' center conductor. The nut should thread freely and fully engage the mating threads by hand. If encountering excessive resistance, remove the connectors to investigate the problem.

After hand tightening the nut, tighten the connector to the specified torque using a torque wrench, while using a wrench to prevent the mating connector from rotating if necessary. Ensure the proper torque spec is used, as excessive torque can deform the connector, while insufficient torque can result in incomplete mating and poor performance. This step is especially important with higher frequency connectors, as slight mechanical changes will have more of an effect with the shorter wavelengths of higher frequencies.

In situations when mating compatible connector types, such as a 3.5mm and 2.92mm connectors, the lower of the two torque specs should be used.

2.2 Connector Care

Connectors are an integral part of a system, and degradation or damage of a connector will affect the overall system performance. Proper connector care is crucial to ensure proper system operation.

Some steps that can be taken to protect connectors are:

- Inspect and clean connectors on a regular basis.
- When not in use, dust caps should be installed on connectors and adapters to protect from damage, debris, and contamination.
- Avoid touching mating surfaces.
- Store connectors in a clean and dry environment, and in a protected manner, not loosely togther in a container.
- Do not drop connectors, as this can cause physical damange, especially with precision air-direlectirc high-frequency connectors.

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In addition, implementing use of a connector saver can also be a good practice. In usages where cables and connections are frequently changed, commonly in a production or manufacturing environment, a connector saver will take the wear of normal use. The connector saver acts as a sacrificial wear item, thereby protecting the connector on the test equipment. This allows replacing only the damaged/worn connector saver when needed, rather than having the expense and downtime of connector replacement on the test equipment, or replacement of a cable.

It is important to note that the addition of a connector saver, while mechanically beneficial, is an additional pair of connections in the RF path and may have an adverse effect on the system performance, and could increase measurement uncertainty. Measurements should be taken to characterize the effect of the addition of a connector saver.

Ultimately, due to the mechanical processes involved in connector use, with mating and de-mating cycles, connectors will wear, and performance will degrade. Following proper care, maintenance, storage, and mating technique will maximize the usage cycles.

2.2 Adapters

Using an adapter to convert between connector types needs to be done with care, and with the understanding of the limitations involved. Simply the fact that an adapter is available does not imply that it is appropriate for use in your application. Each connector type has maximum frequency and power limits, and the application needs to operate within both of these limits, for both of the connector types.

Maintaining the same connector type in the RF chain as is used on the amplifier output is a good approach. Using an adapter to convert to a different connector type needs to be done with care, considering the maximum possible frequency and power both of the connector types could be subjected to.

2.3 Connector Grades

For a given connector type, not all connectors are made to the same standards of precision. Some connector types, primarily the higher-frequency types, are available in various quality grades. There are three common categories of connector quality that are used in the industry, with variations in design and terminology between manufacturers.

Metrology grade is the highest precision and quality grade connector, and most expensive. These would commonly be reserved for high accuracy applications such as for calibration purposes and use on calibration standards.

Mid-range grade connectors, sometimes called 'instrument grade', have good performance and provide accurate measurements, and are often used on test equipment and in lab use.

The lowest grade of connector, referred to as 'commercial', or 'production', or 'field' grade connector, has looser tolerance and lower performance, and is the least expensive connector grade. These are most commonly used in production and manufacturing.

Note that the maximum frequency rating of a connector type may vary depending on the grade of the connector, thus use care when operating at the higher end of the connector frequency rating to ensure the connectors being used are of a grade to support the frequency in use. For details of the design and performance differences between grades, reference the manufactures product information.

2.4 Inter-Series Compatibility

Although not intuitive, some connector series families are compatible with other connector series, and can be physically connected. However, each series carries its own power and frequency limits.

The 2.4mm and 1.85mm connectors are mechanically compatible and can be inter-mated.

The 3.5mm, 2.92mm/'K', and SMA connectors have the same basic dimensions, and can inter-mate. However, the looser SMA tolerances can lead to damage to the high-precision 3.5mm and 2.92mm connectors. This primarily applies when using a male SMA connector, where variations in the male center pin diameter or height could damage the female jack of the mating connector.

In addition, when connecting an SMA to a 3.5mm or 2.92mm connector, it is very important to carefully align the connectors before mating to avoid damaging the center contacts. Some SMA connectors are categorized as 'precision SMA', which are manufactured to tighter tolerances, allowing safe mating to 3.5mm and 2.92mm connectors. Regardless, the mating process needs to be performed carefully.

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2.5 Conntector Gender

Connector gender is often assumed to be determined by the gender of the connector center contact, however this is not the case. Although these do agree in many cases, better practice is to understand the different connector configurations possible, and how connector gender is determined. The connector gender designation is not defined by the center pin, but rather follows the connector body configuration. The center pin will then determine if the connector is Standard Polarity (SP) or Reverse Polarity (RP).

The connector with a coupling nut/shell with internal threads is designated as a male connector (or plug). The connector with a body that has external threads is designated as a female connector (or jack).

Once the connector gender is identified, look to the center conductor configuration to determine if the connector is SP or RP. A male connector with a male center pin, or a female connector with a female center socket, is an SP connectors, since the body and center conductor genders match. SP connectors are the common conventional configuration encountered.

A male connector with a female center socket, or a female connector with a male center pin, is an RP connector, as the body and center conductor genders are different. RP connectors are less commonly encountered and were originally developed for use in specialty applications to discourage alteration of the equipment.

Below are images of standard polarity SMA and Reverse Polarity SMA connectors to visualize the configurations.

	SPSMA	RPSMA
Male		
Female		

Caution needs to be used in situations where RP connectors are available, as although SP and RP connectors can be physically mated, this would result in either damage to the center pins due to being forced together, or no continuity through the connection if two female center sockets are mated.v

2.6 Connector Gauging

The function of coaxial connectors depends upon the physical interface between the mating connectors. To achieve optimum performance, the center conductor height is very important. If the center conductor is recessed into the connector body beyond the allowable tolerance, the connection will suffer from degraded performance. However, if the conductor protrudes beyond the tolerance, performance may suffer in addition to possible physical damage. A damaged or out-of-tolerance connector may cause damage to each connector it is mated to, spreading damage to other connectors and affecting measurement accuracy as well as causing repair expenses.
For these reasons, gauging connectors is a recommended practice to confirm connector dimensions are within acceptable tolerance. Gauge kits are available for most connector types.

Establishing a regular gauging program for cables and equipment is recommended to detect out-of-tolerance conditions and connector damage or wear. Cleaning and inspection should be performed before gauging. Additionally, it is good practice to gauge any connector before first use in the facility, such as cables, adapters, and connectors on equipment.

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2.7 Connector Specifications

The table below further defines maximum frequency, power, and coupling torque parameters for the RF connectors covered in this reference guide.

Maximum frequency, power and coupling torque

Connector Type	Maximum Frequency (GHz)	Maximum CW Power @ Max, Frequency (Watts)	Coupling Torque (N-cm)	Coupling Torque (in-lb)
2.4 mm	50	15	90	8
2.92 mm/K	40	20	90	8
3.5mm	34	45	90	8
SMA precision	26.5	70	57	5
BNC	4	70	N/A	N/A
TNC	18	250	N/A	N/A
Type N	11	150	135	12
Type N precision	18	250	135	12
Type C	12	440	N/A	N/A
7-16 DIN	7.5	820	226	20
7/8 EIA	6	920	N/A	N/A
1 5/8 EIA	3	3200	N/A	N/A

2.8 RF Cables

Having selected RF connectors using the guidelines provided above, the next logical step is the selection of appropriate RF cables. There are a myriad of coaxial cable types to choose from. As with the RF coaxial connectors, coaxial cables are classified by physical characteristics as well as electrical parameters. Both flexible, semi-flexible or rigid armored cables are available. Electrical parameters such as characteristic impedance (50 and 75 ohms are common values), insertion loss, maximum voltage and maximum power capabilities must be considered. The application will determine the proper cable choice. Some applications require low loss cable to maximize power transmission. Other applications require flexible cables, perhaps without restrictive armor, for user friendliness. Coaxial cables contribute to the overall performance of the RF assembly and can become a limiting factor for maximum frequency and power handling capability. It is important to keep in mind that any cable assembly will be limited both in frequency and power handling capability by the lowest power rated and frequency capable RF connector.

To facilitate cable selection, AR/ RF Microwave Instrumentation has developed a line of high quality, built-to-order coaxial cables. These low loss cables are characterized by very low VSWR and are tailored to the end users specific needs. There are four basic series; CC1, CC2, CC4 and CC5. Custom lengths are available in 0.1 meter increments with a variety of matched connectors.

CC1 Series – These are armored, low loss cables for applications to 18 GHz. They are available with SMA, TNC, N or 7-16 connectors.

CC2 Series – These are armored, low loss cables for applications to 40 GHz. They are available with 2.4mm, 2.92mm, 3.5mm, SMA, TNC or N connectors.

CC4 Series – These are high power, flexible cables for applications to 6 GHz. They are available with N, 7-16, DIN 7/8 EIA, or 1-5/8" EIA connectors.

CC5 Series – These are low loss cables compatible with higher power applications to 11 GHz. They are available with N, 7-16 DIN, C, or SC connectors.

Summary

RF coaxial connectors and cables are often forgotten components of RF systems. It is important to review all of the specifications discussed when selecting the right RF coaxial connector for your specific application. As mentioned, thinking about the connectors does not end after the selection process. Continued proper care and maintenance will help to ensure accurate system operation. While they may not command the interest and attention of the more costly system components, improper selection of RF coaxial connectors and/or cables can render a sophisticated system ineffective, so it is important to carefully select connectors and cables that are best suited to accommodate your specific applications.

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