

## Use of Probes in Radiated Susceptibility Testing

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## EM field Probes/Sensors

- Field sensor basics
- radiated susceptibility (RS) test
- Types of probes
- Calibration/Application



## Definition (IEEE 1309)

- Field Probe
  - An electrically small field sensor or set of multiple field sensors with various electronics (for example, diodes, resistors, amplifiers, etc.). The output from a field probe cannot be theoretically determined from easily measured physical parameters
- Field Sensor
  - An electrically small device without electronics (passive) that is used for measuring electric or magnetic fields, with a minimum of perturbation to field being measured.
  - Can be theoretically determined, and traceable to NIST



## Typical EMC probes

- Electric probes
  - Dipole / monopole sensors
  - Diode detector
  - Thermal detector
  - Self-contained
  - Stem with a hi-R line that connects electronics to the probe head



## E field probes



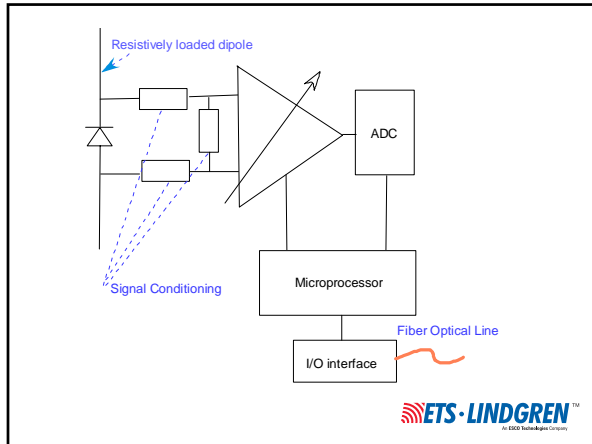
- Typically works from 10 KHz to GHz range (40 GHz)
- EMC probes are designed to have a flat frequency response.
- EMC probes are typically designed with three orthogonal sensors for isotropic response
- Broadband devices (respond to signals at all frequencies in their operating band)
- Minimal disturbance devices (Fiber optical link)



## Basic Theory of Operation

- Diode Sensor/Probe
- Thermal (thermistor) Sensor/Probe
- Laser/Crystal optical probe





## How does an Electric Field Sensor work?

- Antenna elements (resistive loaded)
- Diode rectifier or thermal sensor
  - Linear region (proportional to E-field)
  - Square-law (proportional to field density)
- DC Filter
- Gain blocks - adjustable for wide dynamic ranges, such as 0.5 V/m to 900 V/m
- A/D conversion
- Micro-processor, and serial optical interface



## Terms

- Frequency Response
- Isotropic Response (Isotropicity)
- Linearity Response (dynamic range response)
- Difference from antennas



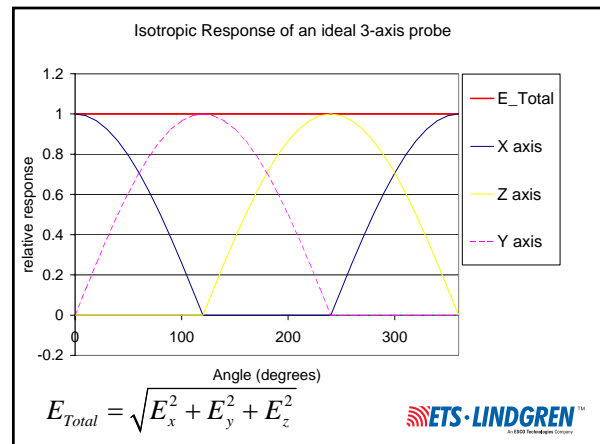
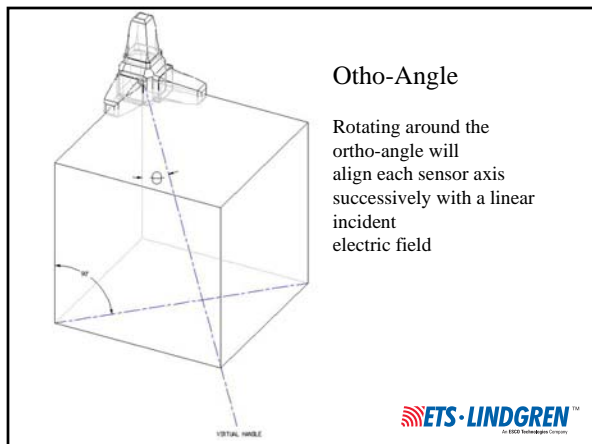
## Isotropic Response

- Probes are typically designed to be isotropic. There are three orthogonal axes. The field are summed based on:

$$E_{Total} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

- Figure of merit: Anisotropy

$$A = 10 \log_{10} \left[ \frac{S_{max}}{\sqrt{S_{max} S_{min}}} \right]$$



## Linearity ...

- Most EMC probes have three individual axes. Each axis has a built-in linearity correction table for CW signals (meaning probe reading becomes strictly proportional to the applied field after linearity correction for each axis). The result is then summed by the processor in the probe, or by a computer or a readout unit once they obtain the readings for all axes.
- Modern probes have the correction table (CW only) built into the probe, so a user need not to correct for this manually. This needs to be checked during routine calibration, and reload if necessary!



## Linearity

- Thermo probes are true RMS detector devices. It is safe to sum all three axes using analog means.
- Diode detectors are only RMS detectors at low field levels (e.g. <15 V/m). At higher field levels, they are typically average detectors. They respond to the average value of the rectified RF signals. Summing three axes using analog method can produce large measurement uncertainties, which can not be corrected for later on.



## Mathematically Speaking...

$$E_{Total} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

The simplest calibration (square-law)

$$E_{Total} = \sqrt{k(V_x + V_y + V_z)}$$

A much more comprehensive calibration (including dynamic range response linearization)

$$E_{Total} = \sqrt{k_x V_x (E_x) + k_y V_y (E_y) + k_z V_z (E_z)}$$



## Pay Attention to...

- Range Switch (how its handled)
- Linearity
  - Internal lookup table.
  - Calibration procedure SHOULD adjust the linear response of a probe. (calibration vs. characterization)
  - Unlike thermal probes, diodes are typically NOT true RMS detectors (under large signals), but are calibrated such that probes read correctly under CW conditions.
- Broadband device
  - No frequency discrimination in band

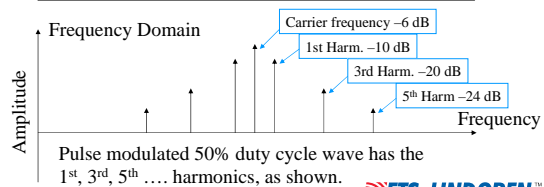
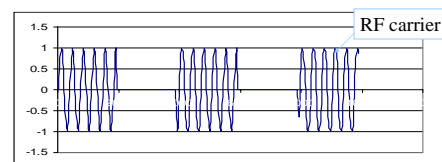


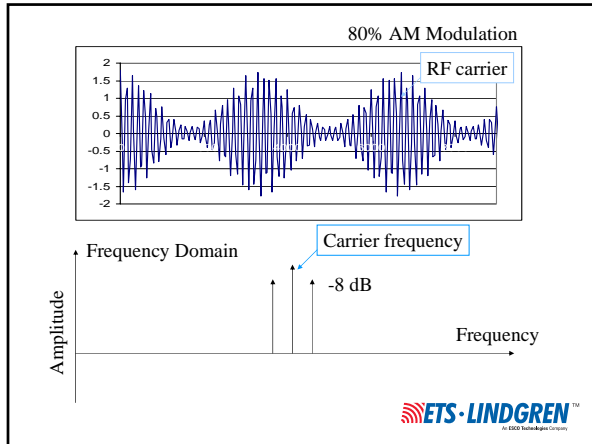
## Probe Correction Factors

- Frequency response: typically a user obtains CW frequency response from a calibration lab (in forms of correction factors). End user should correct for frequency response either manually or by a computer. These frequency dependent corrections can not be applied unless the frequency is known by the probe.
- Note that in MIL-STD 461E RS103, 50% pulse modulation (1 kHz) is applied, instead of CW. Additional correction is needed.
- Linearity response for CW is typically already included in a probe, and an end user does not need to apply corrections manually.
- What about modulated signals?



Time Domain 50% Duty Cycle Pulse Modulation





### Additional Power Requirement 80% AM

$$U(t) = [1 + m \cos(2\pi f_m t)] \times \cos(2\pi f_0 t)$$

$m$  ... modulation index = 0.8 for 80% AM

$f_m$  ... modulation frequency

$f_0$  ... carrier frequency

- Modulation index indicates by how much the modulated variable varies around its 'original' level.
- For 80 % AM, the max output voltage is 1.8 times the CW signal. Consequently, the maximum output power required from an amplifier needs to be  $20 \times \log_{10}(1.8) = 5.1$  dB more!



### Modulation Corrections

- MIL-STD 461E RS103: Additional Calibration is required for modulated signal
  - Measure the probe under CW signal and adjust the signal until the probe reads at the upper end of the scale. Note the reading.
  - Turn on the modulation (1 kHz pulse 50% duty cycle), making sure the peak voltage value stays the same as the CW, and note the reading again
  - Division of the two readings is the modulation correction
  - This correction factor is in addition to CW correction from the manufacture or calibration lab.

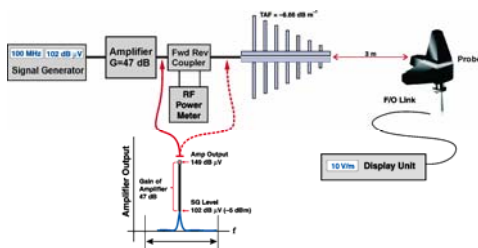


### Commercial (IEC) Immunity

- For commercial immunity measurements (IEC-61000-4-3), CW signal is used in the calibration step. Modulation is only turned on during actual product measurement.
- Probes are never used to measure modulated field, thus only CW correction is needed.



### Typical Commercial Immunity Test setup



### MIL-STD 461E RS Testing

- From 2 MHz – 1 GHz, electric field sensors are required.
- For > 1 GHz, either field sensors or receive antennas may be used.
- Note that using a receiving antenna or a sensor is not equivalent in the standard
  - Total field (incident + scattered) for using a sensor (in-situ)
  - Empty field (incident only) for using an antenna (substitution)

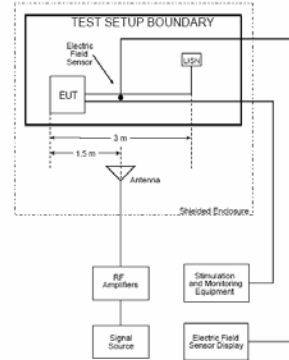


## MIL-STD 461E RS Testing

- How do probes respond to non-CW signal?
  - Probes respond differently with or without modulation. Thermal probes or diode probes under low fields are power (RMS) detectors. Diodes become linear under higher field levels, and are not power detectors anymore.
  - Diode probes under high fields are more complicated. Depending on probes, different probes can respond to modulation differently. Correction factors for a certain modulation need to be measured specifically.



Typical MIL-STD RS Setup



## Field Generating Devices

- Field Generating Devices:
  - TEM devices (TEM cell, GTEM cell, tri-plate, parallel plate, strip lines etc.)
  - Antennas (biconical, log periodic dipole arrays, hybrid, double-ridged waveguide horn, standard gain horns etc.)
  - Reverberation chambers
- Typically, TEM devices are used at lower frequencies, limited by higher order modes (less than several hundred MHz)
- Antennas: typically 30 MHz and above (efficient antennas become physically large at low frequencies)
- Reverb chambers: >200 MHz (limited by mode density: size of the chamber)



## RS103 setup

- Probes position: 1 m directly at the boresight of the transmit antenna. Minimum 30 cm above the ground plane. Avoid placing probes at the corners or edges of EUT, because of the large scattered field.
- <30 MHz, only horizontal polarization
- >30 MHz, both horizontal and vertical polarizations are required
- Electric field levels are specified in RS103, so electric field sensors are preferred and needed under near field conditions.



- 2 MHz to 200 MHz:
  - For test setup boundaries < 3 m, center the antenna between the boundaries
  - For test setup boundaries >3 m, subdivide into 3m wide sections.
- 200 MHz-1000 MHz, enough positions such that half power beam width (HPBW) covers each EUT enclosure and first 35 cm of cables and leads.
- > 1GHz, HPBW covers EUT + 7 cm cables and leads



## RS103 Test Level

- Test levels vary depending on applications. For example:
  - 200 V/m from 2 MHz – 40 GHz for Aircraft (external or safety critical)
  - 10 V/m from 30 MHz – 40 GHz for Ships below deck
- Field probes may operate under square law or linear region. The linearity corrections in the probes should be checked.
- Recommend modulation corrections be calibrated at the intended test level



- There is no implied relationship between RS103 and RE102 limit. RE102 is primarily for protecting antenna-connected receivers. RS103 limits are based on levels expected to be encountered in actual applications.
- Circularly polarized antennas are not allowed (such as log spiral).

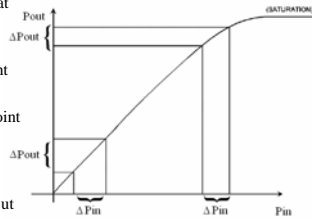


- From 10 kHz – 2 MHz, RS103 is not imposed on army aircrafts. It is covered by CS114.
- If CS114 is not imposed for a particular application, RS103 should be tailored to cover 10 kHz – 2 MHz.



## Know your power amplifier

- What you see is not always what you get
  - Max output power
  - 1 dB gain compression point
  - Harmonics
  - Third Order Interception Point
  - Noise Figure
  - For CW signal, harmonic contents can be significant (typically no intermods). But for modulated signals, more than one frequencies exist.



## Amplifier Noise

$$NPD = K \square T \square G \square NF$$

*NPD* – Noise power density (W/Hz)  
*K* – Boltzmann's constant ( $1.38 \times 10^{-23}$  Joules/K)  
*T* – Temperature (Kelvin)  
*G* – Gain of the amplifier  
*NF* – Noise Figure

- Be careful when computing output noise power – *NF* is not proportional to input noise. It depends on the particular value chosen for the input noise power (*kT<sub>0</sub>B*). It is safer to use noise temperatures concept.

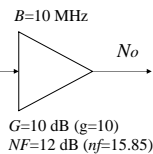
$$NF = 1 + \frac{N_{added}}{N_{input}} = 1 + \frac{N_{added}}{kT_0B}$$

- Can you measure the noise floor with no input to amp? Generally yes (exception: class C amplifier, which is not used in immunity tests)



$$N_i = kT_a B = -100 \text{ dBm} = 1e-13 \text{ W}$$

$$T_i = N_i / kB = 1E-13 / 1.38E-23 * 10e6 = 725 \text{ Kelvin}$$



### Equiv. noise temp:

$$T_e = (nf-1)T_0 = (15.85-1)(290) = 4306 \text{ Kelvin}$$

### Output noise:

$$N_o = k(T_e + T_i)BG = (1.38e-23)(4306 + 725)(10e6)(10) = 6.94e-12 \text{ W} = -82 \text{ dBm}$$

When starting at noise levels other than *T<sub>0</sub>*, DO NOT add dB values directly to obtain output noise

$$N_o = N_i + G + NF = -100 + 10 + 12 = -78 \text{ dBm}$$

This is wrong! Because by definition *NF* is based on *T<sub>0</sub>* at input



## Estimating Noise

- Example 2-4 GHz TWT amp:
  - NPD = -73 dBm/Hz
  - BW = 2 GHz ( $10 \cdot \log_{10}(2e9) = 93$  dB Hz)
  - Total noise power across the band = 20 dBm = 0.1 W
- Assuming no cable loss, and antenna gain = 10 dBi (numerical gain *g* = 10), also assume the probe is a true power detector):
  - The noise power alone will cause the probe to read at 1m away from the antenna

$$E = \sqrt{30 P g} = \sqrt{30 \times 0.1 \times 10} = 5.5 \text{ V/m}$$

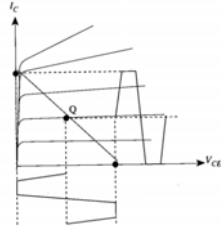
If probe reads 20V/m, the field at the desired frequency is

$$E = \sqrt{20^2 - 5.5^2} = 19.22 \text{ V/m} \quad (-0.35 \text{ dB})$$



## Power Amplifier Max Output

- Max power output of an amplifier is typically based on CW with a 50 ohm load
- A better measure of an amplifier is the maximum output voltage. For wideband signals, the resulting time domain peak output voltage should not exceed the specified maximum peak voltage for CW. Beyond this point, compressions and clippings occur (amplifier becomes nonlinear)



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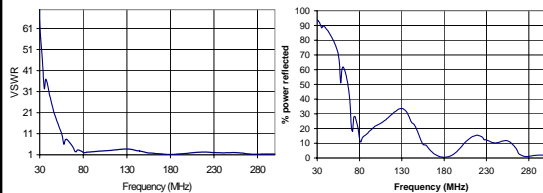
- For pulse modulation per MIL-STD 461E, because the peak voltage is the same as CW, additional power is not required.
- For 80% AM per IEC 61000-4-3, the peak voltage is 1.8 times the CW, thus the power required is  $(1.8)^2 = 3.24$  times the CW (5.1 dB more)

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## Know Your Antennas

### Reflections from Antennas

ETS Model 3109 High Power Biconical Antenna



EUT is only 1 m from the antenna. Below ~60 MHz, EUT is in the reactive near field (non-radiating quasi-static field). Most power is returned to amplifier.

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- Make sure amplifier can withstand the large reflected power (VSWR tolerance).
- In EMC antenna catalogs, gains are derived from AFs (apparent gain) with mismatch already included. When estimating power requirements, there is no need to include additional power.
- An intense field is possible in the reactive near field albeit the antenna's low efficiency, but E-field dies off much more quickly as a function of distance ( $1/r^3$ ) than in far field. (Analogy: E-field close to a capacitor)
- The field is mostly electric, with little magnetic field contents. This is different from a TEM cell, GTEM, or far field testing ( $E/H=377 \Omega$ ).
- Far field gain (or antenna factor) is not a good indicator for field generation from the antennas in the reactive near field ( $\sim \lambda/2\pi$ ).
- One should use an ISOTROPIC field probe to measure the electric field strength. The E-field has large longitudinal components.

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## ARP 958 Antenna Factors

- 1 m antenna to antenna separation.
- Based on far-field assumption which is not met for much of the frequency range for biconical antennas.
- Strong antenna-to-antenna couplings are not reproduced by antenna-to-EUT couplings. As a result, the measurement results will be antenna dependent (influenced by antenna element sizes and shapes, balun impedances etc.)
- AF values are consistent per ARP 958 (for the given antenna and EUT), but true electric fields are not measured. By reciprocity, true electric field values can not be derived based on ARP 958 AFs. One should rely on field probes.

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## Putting Amps and Antennas Together

- Correctly size an amplifier for output power based on the transmit antenna and test environments
  - Typically biconical antennas can be quite inefficient (and poor match to 50  $\Omega$ ) below ~80 MHz. Pushing the amp hard can mean large harmonics and distortion. Consider a different antenna.
  - Be aware of amplifier foldback under mismatches (class AB). Amplifier power ratings are based on matched loads. Max linear power is reduced under mismatched loads.
  - Commercial radiated immunity standards start at 80 MHz at low field levels
  - In MIL-STD 461E tests, test levels can be 200 V/m at 30 MHz (large field and bad match!). Use class A amps, and avoid class AB.
  - Add cable loss in your budget
- Making sure the spectral purity of the output signal (may need harmonic low pass filters)
- Again, probes do not know frequencies and signal purity. We must check the test conditions.

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## Test Environment

- Anechoic Chamber
- Fixtures
- Coupling to the environment



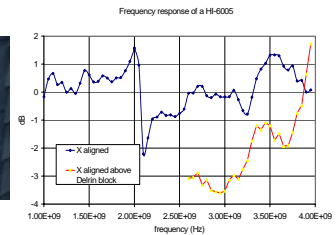
## Anechoic Chamber

- IEC 61000-4-3:
  - Result based spec: 75% points fall in 0 to +6 dB in a uniform area 1.5m X 1.5m. Absorbers on all sides (including over ground plane) are likely needed to achieve the requirement for all frequencies.
- MIL-STD-461E:
  - Semi-Anechoic chamber (no floor requirement).
  - Max absorber reflectivity (normal incidence? Not spec'd; absorber distance to EUT not spec'd)
    - 80-250 MHz –6 dB
    - >250 MHz –10 dB



## Probe Holder/Fixture

- They are in close vicinity of the probe. These factors are important:
  - Material property (dielectric constant, dissipation factor)
  - Size
  - Position
- How about placing probe directly on the tabletop? Tripod?



Effects from a 3"x2"x0.75" Delrin Block  
Er=3.7



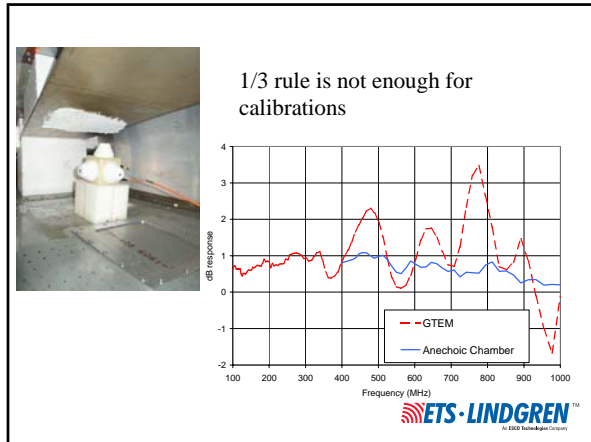
- Probes are calibrated with minimal size, low dielectric supports
- Users should do the same during immunities testing to minimize measurement uncertainties.
- Anechoic chambers used for calibration should be rigorously tested so that they do not introduce additional errors. (periodic ripples in frequency response may indicate non-ideal measurement conditions)



## Probe Coupling with Environment

- Probes are designed to interact minimally with the measuring environments.
- Some couplings can not be avoided for small enclosed test environments, such as TEM cells and GTEMs.
- Rule of thumb: less than one-third volume.
- For probe calibrations, this is typically not enough – less than 1/5 or 1/6.





- calibrate probes in the same orientation as will be used – this can be a misleading proposition.
  - Fixtures and chambers can have significant impact on the measurements – they are typically different at calibration and during usage.
  - In an actual immunity test setup, field structure in a chamber can be quite complex (due to the partial lining on the ground plane, non-ideal performance of the absorbers, limited size chambers, and near-field effects close to the transmitting antenna etc.). This is why an **isotropic probe** is used in the first place. The advantage of an **isotropic probe** is to measure the field accurately regardless the non-ideal factors. A calibration does not repeat all these factors.
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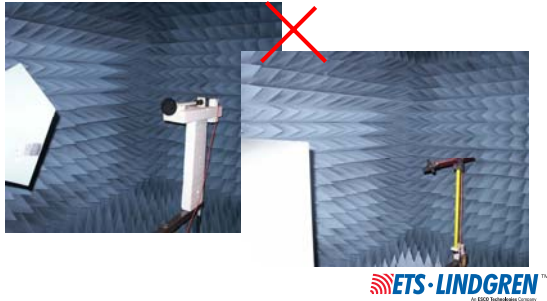
- The best calibration is to qualify each axis thoroughly, and minimize the uncertainties during calibration **and** actual usage.
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- ### Interpolation in Frequency and Linearity Response
- In the gigahertz range, probe frequency response may not be as smooth. Make sure enough frequency points are obtained.
  - Probe linearity response is a weak function of frequency. Comprehensive calibration in linearity responses at different frequencies can be collected, but there will be a tremendous amount of data.
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- ### Channel Isolation
- Ideally all three axis are perfectly isolated, i.e. an axis should not read any thing if applied field is aligned with other axes but not with itself.
  - Channel isolation is typically very large (better than 20 dB) for well-designed probes.
  - If a field is read predominantly by one axis, the finite isolation effect is even smaller.
  - A user should consider align the probe such that one axis reads most of the field.
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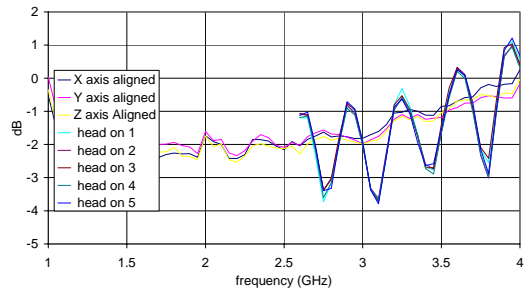
- ### Self-contained vs. Probe on a Stem
- State of the art self-contained probe, such as HI-6005 has an upper frequency limit of 6 GHz. The whole probe is immersed in the field during calibration and application.
  - Probes on stems can be used to as high as 40 GHz. For some calibration setups, not all parts of a probe is in a field (such as in a TEM cell devices). If this is the intended usage, there will be no additional uncertainties. Otherwise, additional uncertainties need to be assessed. Some orientation of the probe is not recommended.
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## Examples



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HI-4433-GRE Frequency Response



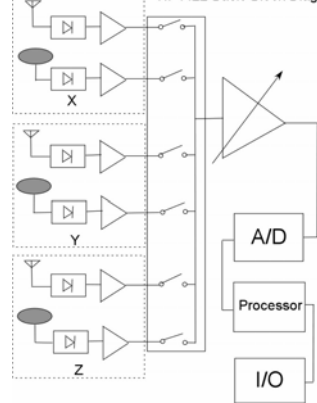
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## Range Setting/Switching

- Older probes require manual switching between ranges. Errors can (and often) occur by using probes outside the dynamic range of a specific setting.
- Modern probes provide seamless range switching which is transparent to the end user.
- Linearity table is different for each range, so linear response should be guaranteed/checked for **EACH** range.

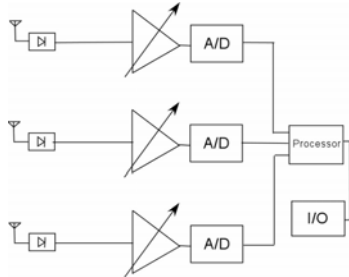
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HI-4422 Basic Block Diagram



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HI-6005 and HI-6105



HI-6005/6105 Basic Block Diagram

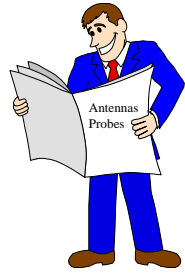
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## Summary

- Many factors affect probe calibrations and applications, including signal purities, fixtures, isotropicity, linearity, temperature, test setups etc... Care must be taken during each step.
- Probe calibrations involves more than characterizations. Follow the recommended practices by manufactures.
- Modern probes can save time and reduce measurement errors (no manual switching between ranges).

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## Discussion



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