PRECISION FILTERS, INC.

Transducer Conditioner Systems ■ Filter/Amplifier Systems ■ Signal Switching Systems

Ground Loop Problems with Measurement Systems and How to Avoid Them

Alan R.Szary

Precision Filters, Inc.

Phone: 607-277-3550

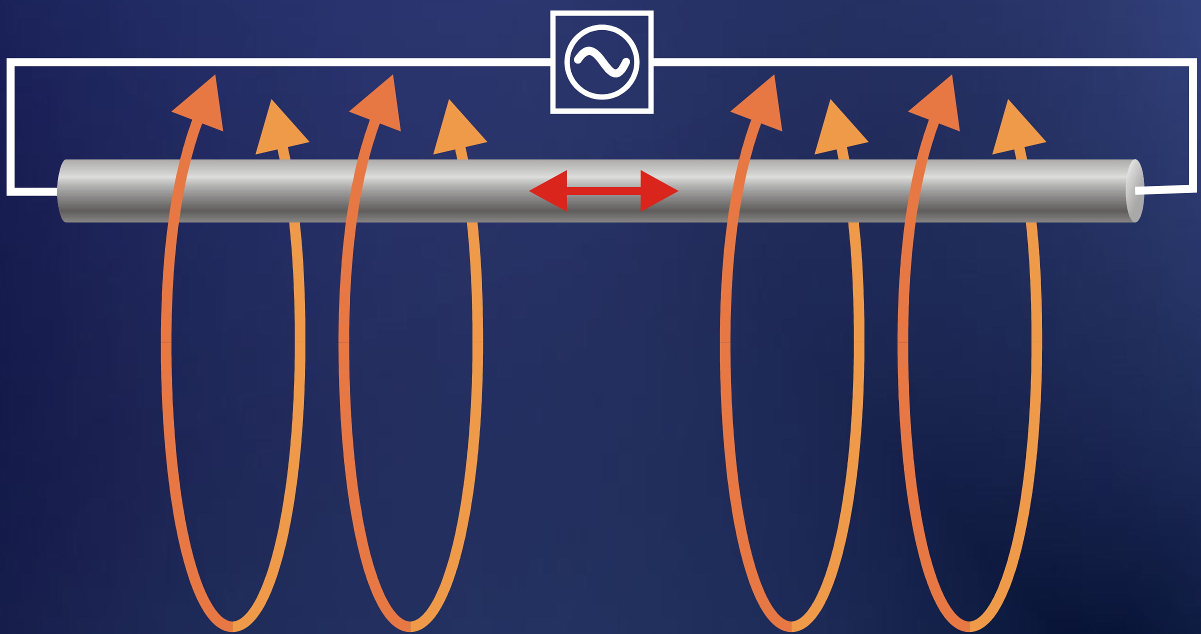
E-mail: pfinfo@pfinc.com

Web: www.pfinc.com

on the New Frontiers of Precision

Electromagnetic Noise Coupling into *Loops*

- Two "Inconvenient Truths" of electromagnetic noise coupling.
- *Inconvenient Truth #1:* Any current carrying conductor will create a magnetic field.



Electromagnetic Noise Coupling into *Loops*

- The magnitude of the magnetic field (B) at any point depends on the current flowing in the source conductor and the distance to the measurement point and is given by:

$$\boxed{B = \mu I / 2\pi r}$$

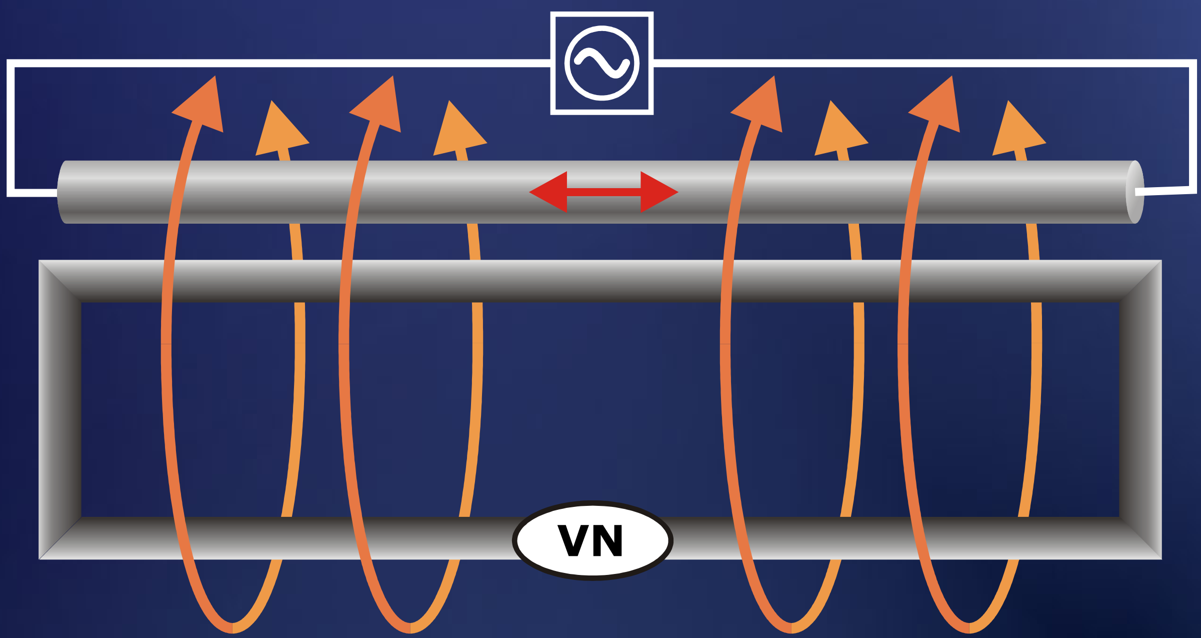
μ = permeability = 4 π X 10 –7 H/m

I = current flowing in source conductor

r = distance to measurement point

Electromagnetic Noise Coupling into *Loops*

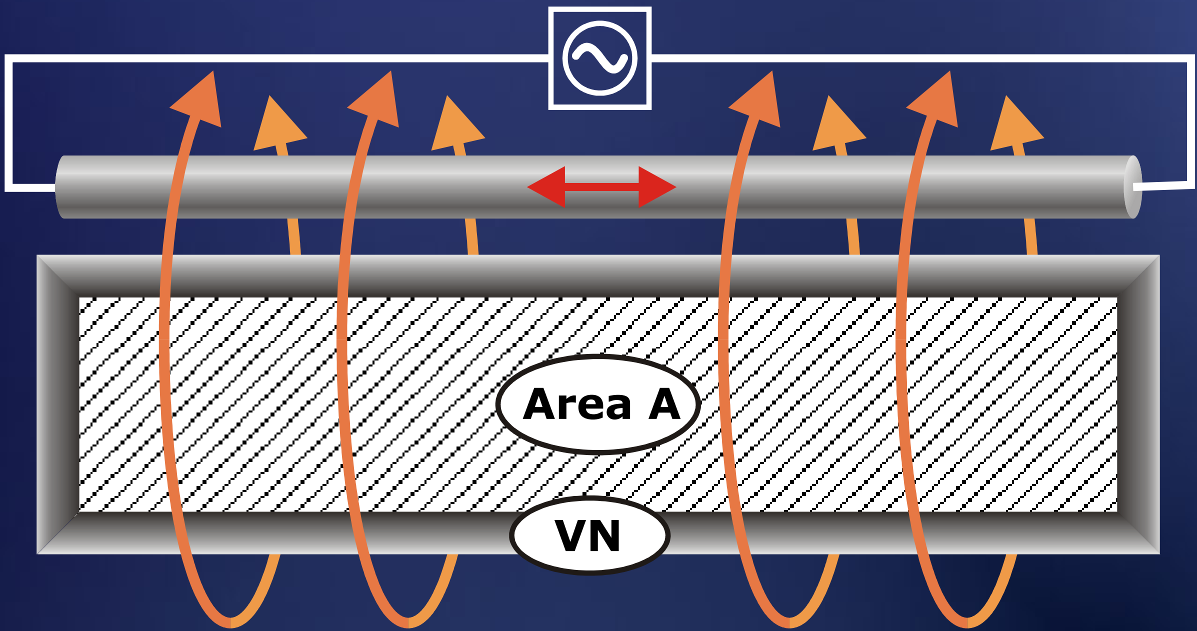
- *Inconvenient Truth #2:* We know from Faraday's Law that any conductive loop being penetrated by a magnetic field will have a voltage induced "within" the loop.



Electromagnetic Noise Coupling into *Loops*

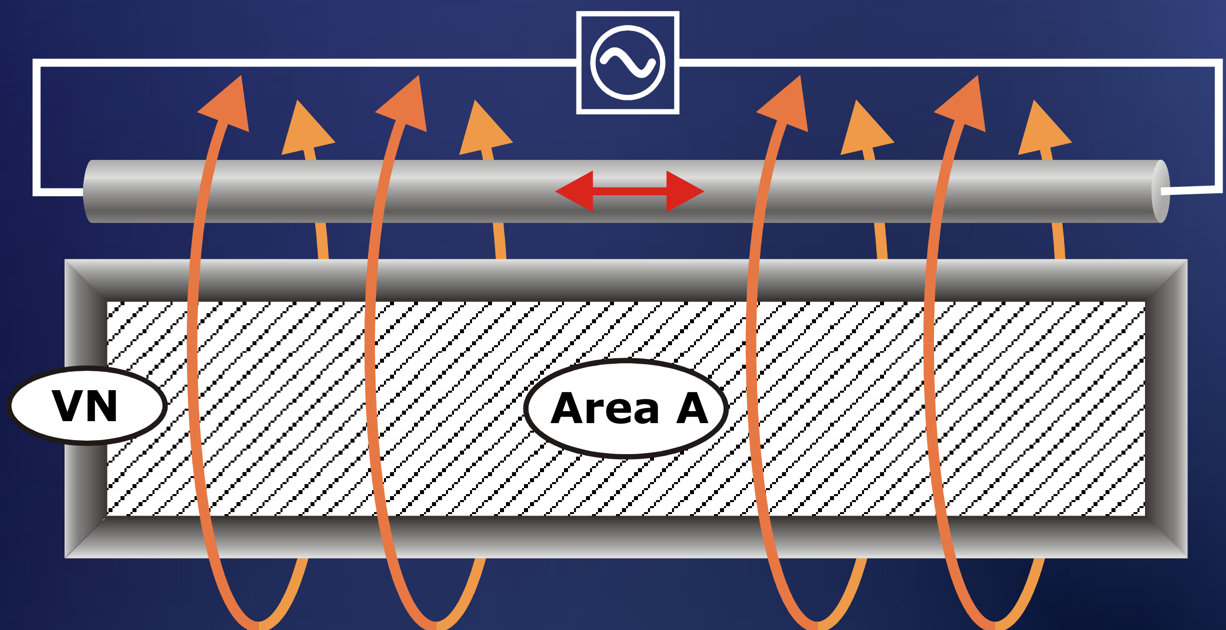
- The magnitude of the induced voltage depends on the overall loop area and is given by:

$$\boxed{VN = jw\ BA \cos\theta}$$

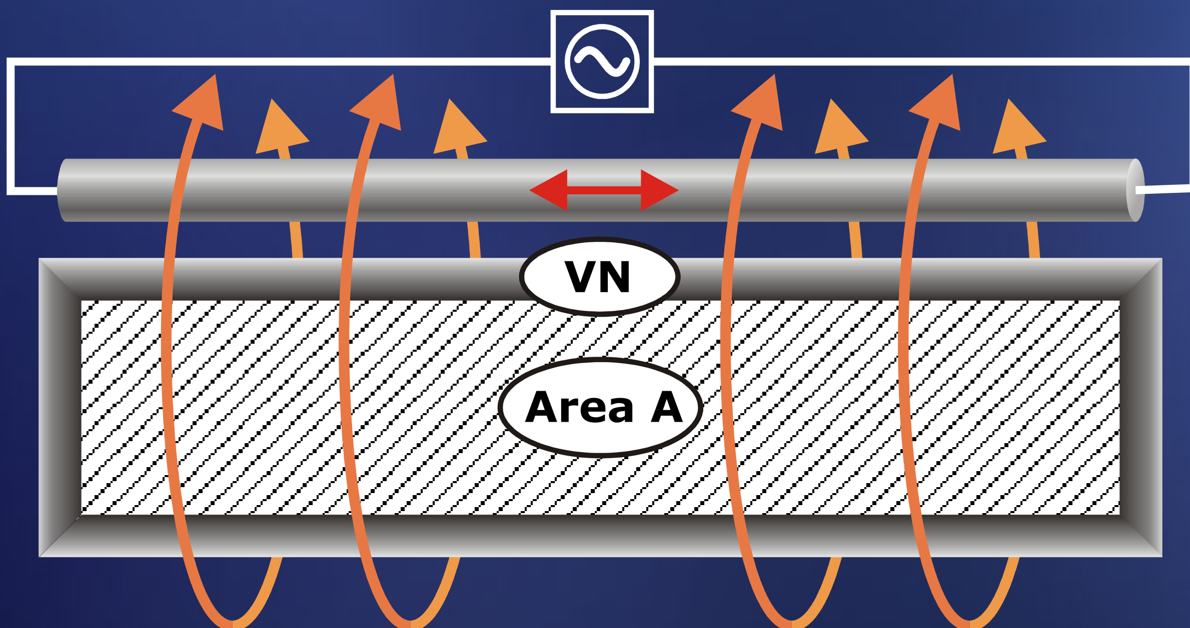


Electromagnetic Noise Coupling into *Loops*

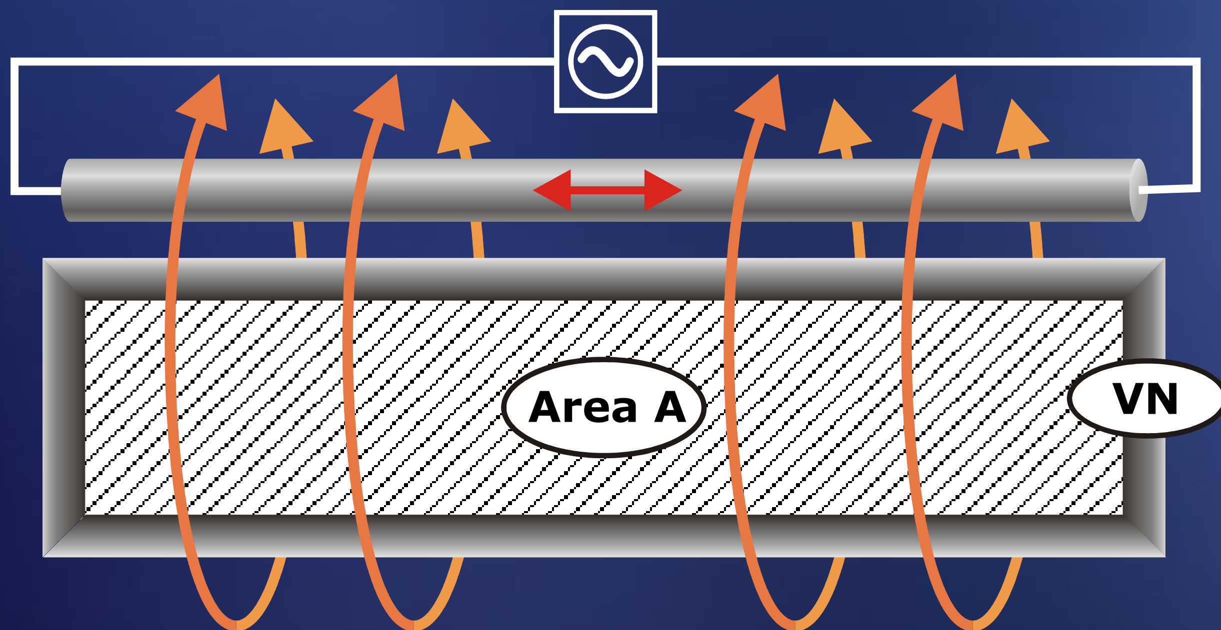
- Adhering strictly to Faradays Laws, the distribution of this voltage throughout the loop can not be exactly determined. For purposes of analysis we refer to this as the “open circuit” or “Thevenin” voltage and place it at any location where the loop is opened up.



Electromagnetic Noise Coupling into *Loops*

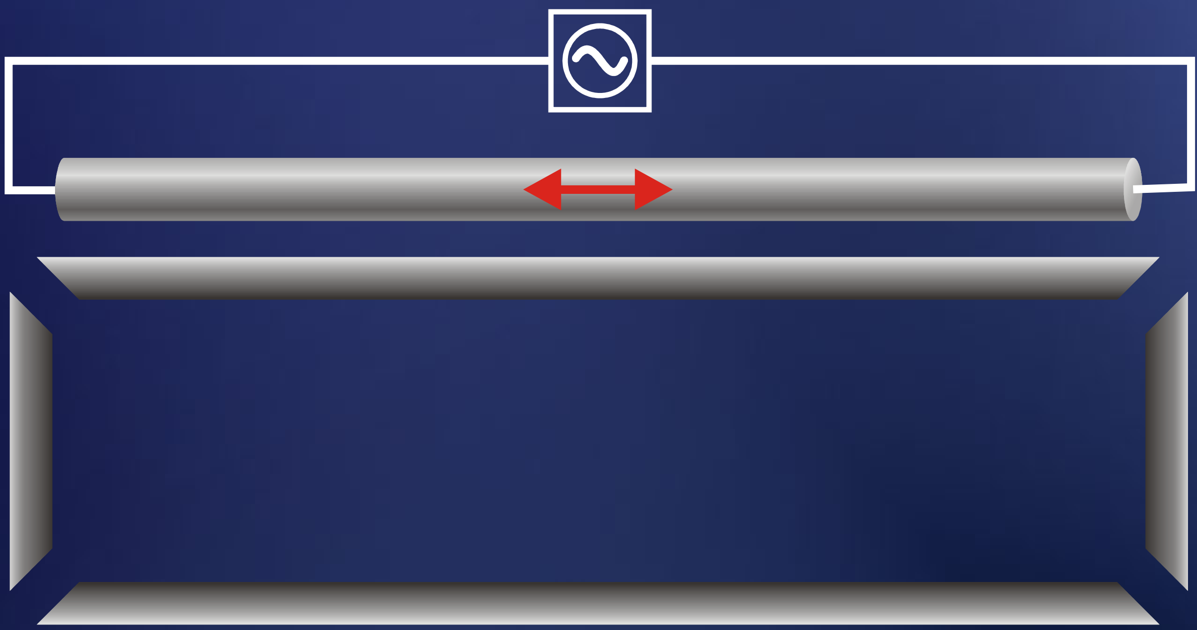


Electromagnetic Noise Coupling into *Loops*



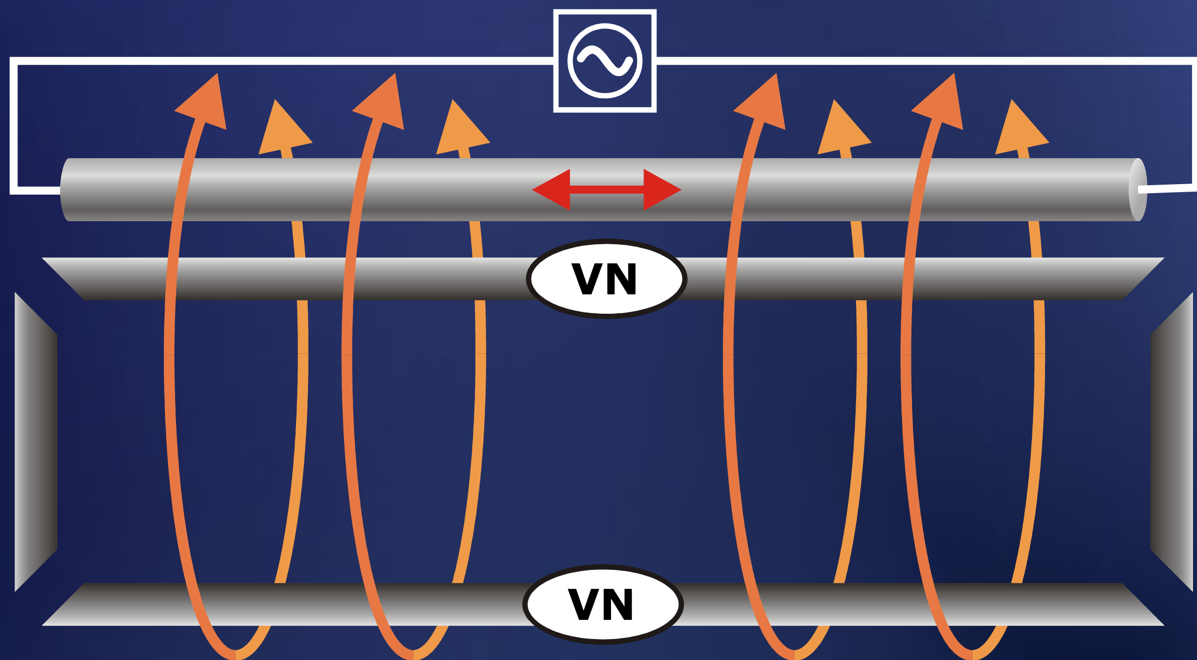
Electromagnetic Noise Coupling into *Segments*

- In order to better analyze a **cabling system** we can exploit the rules of *Partial Inductance* which describes that the Faraday loop can be decomposed into individual (partial) conductive *segments*...



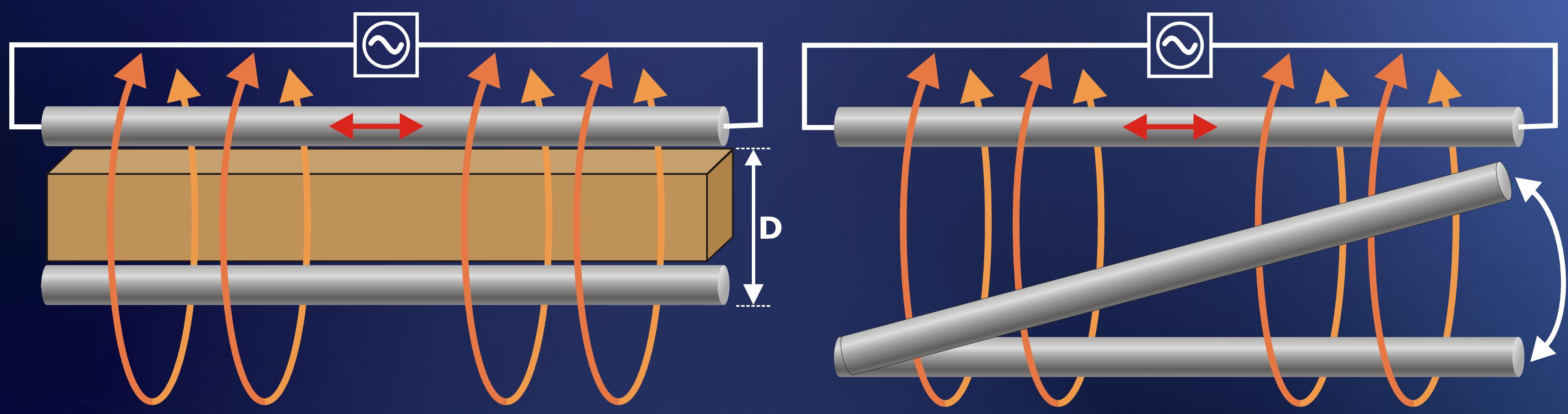
Electromagnetic Noise Coupling into *Segments*

- …and that voltage is induced in any conductive segment exposed to a magnetic field.



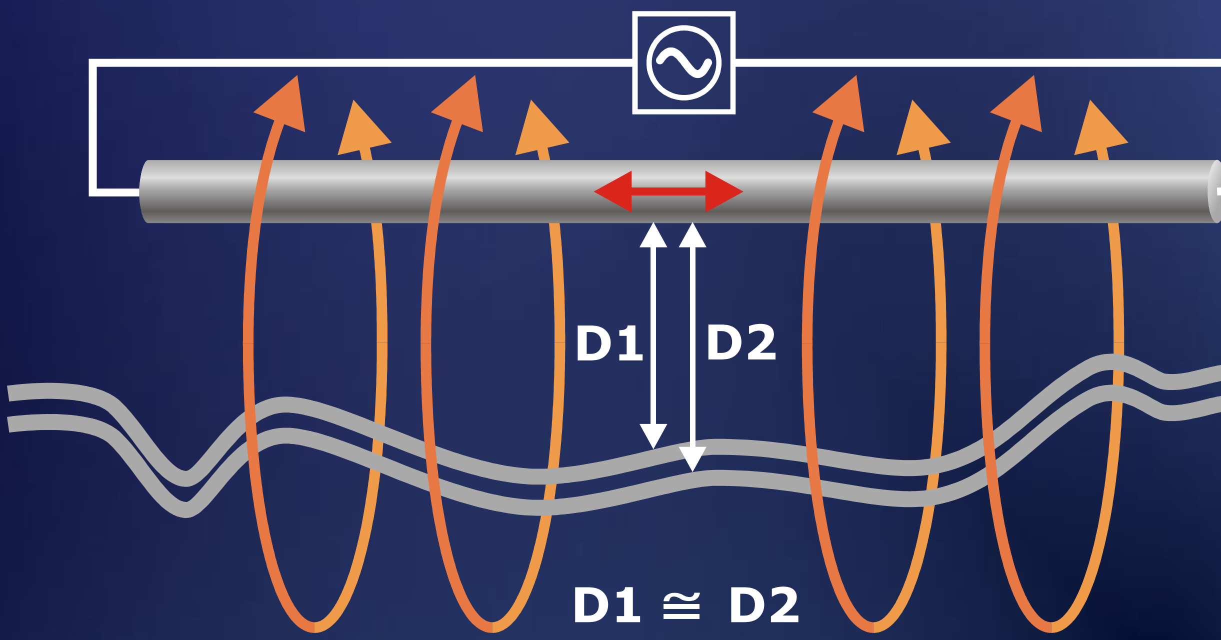
Electromagnetic Noise Coupling into *Segments*

- The induced voltage is dependent on the conductive *medium*, and the *distance* and *angular orientation* between the two conductors. Collectively we will refer to these as the conductor's *spatial geometry*.



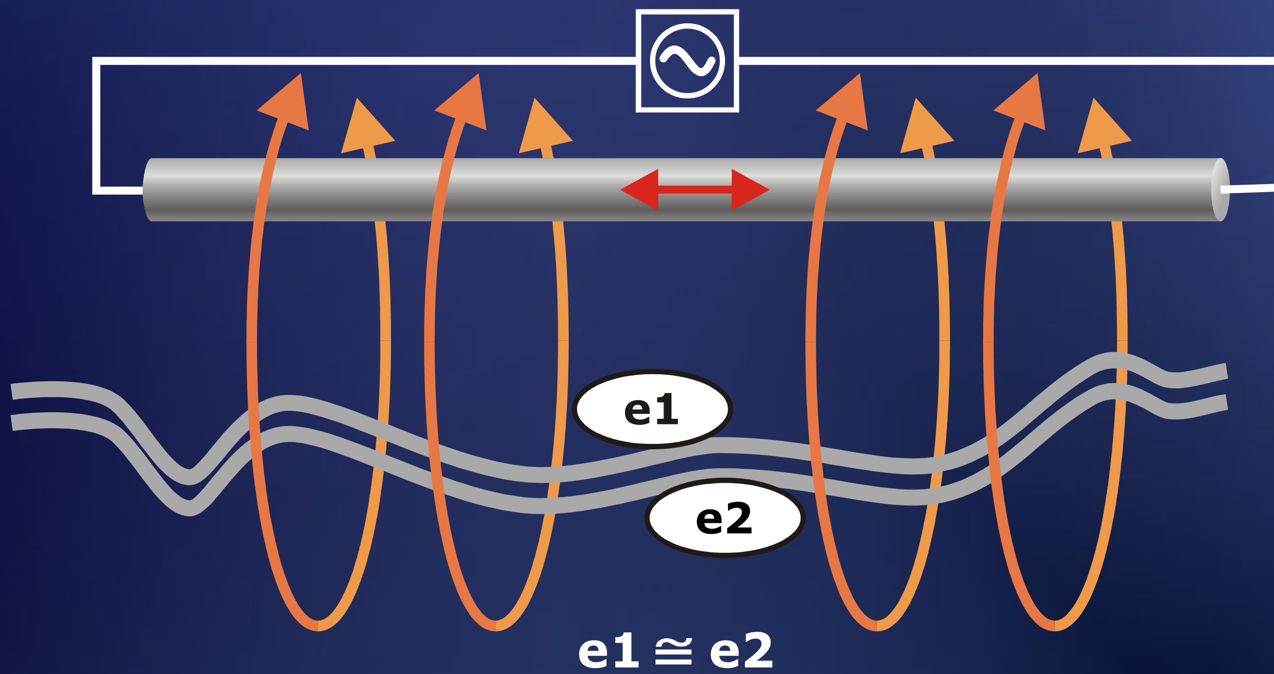
Electromagnetic Noise Coupling into *Segments*

- For the frequencies of interest for modal analysis testing, it is a reasonable assumption that conductor segments within a individual cable will have similar spatial geometry relative to the wavelength of the magnetic field *at every point throughout the cable run…*



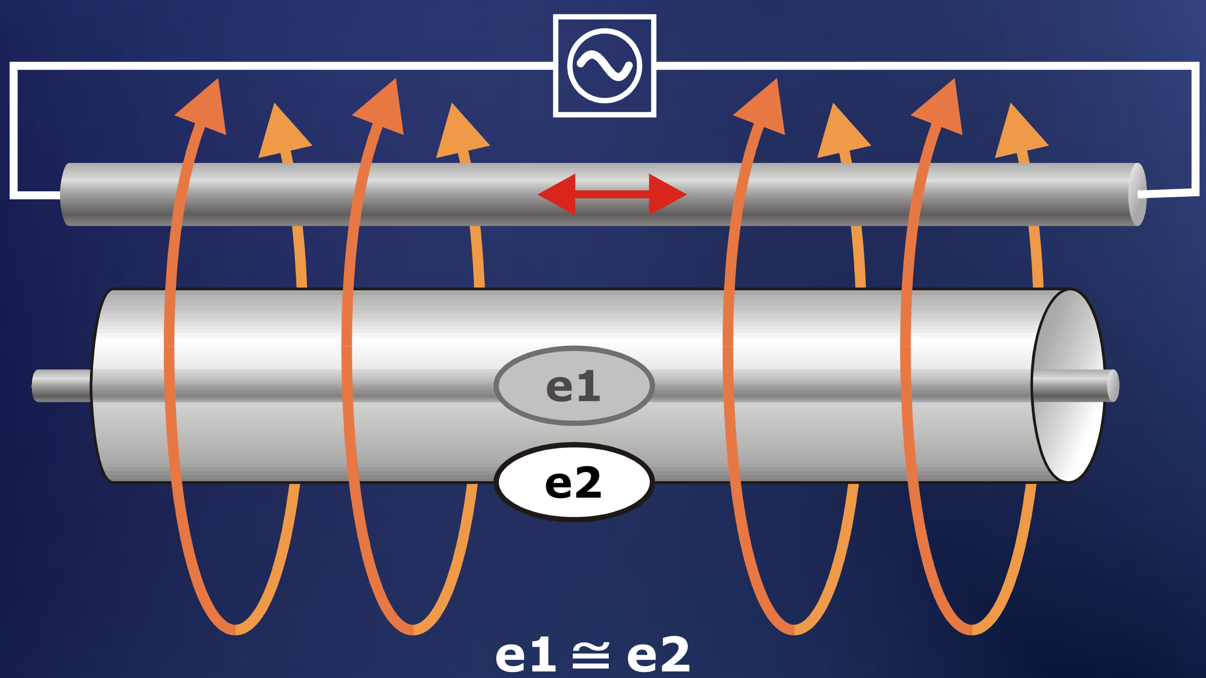
Electromagnetic Noise Coupling into *Segments*

- …and will therefore have nearly equal induced voltages.



Electromagnetic Noise Coupling into *Segments*

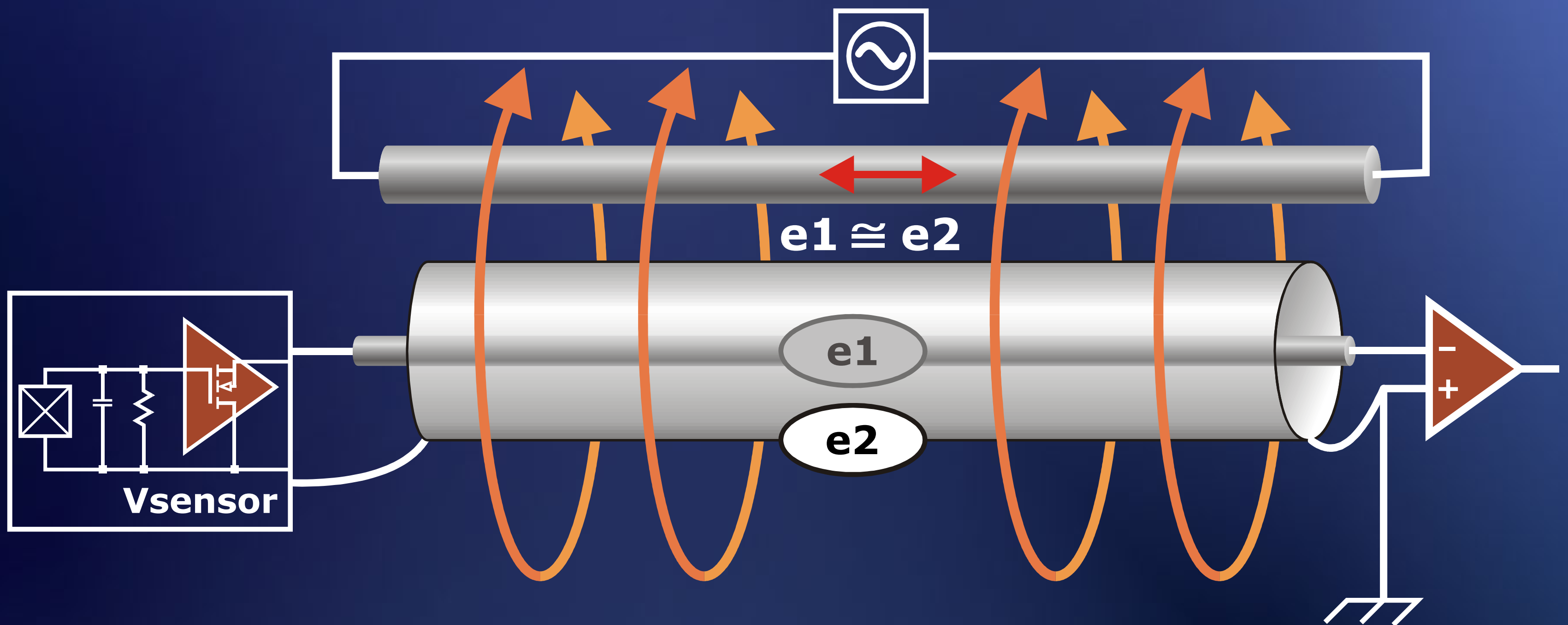
- Relative to the wavelength of the signals of interest, even a coaxial shield is spatially equivalent to it's center conductor.



Magnetic Coupling Errors in Measurement Systems

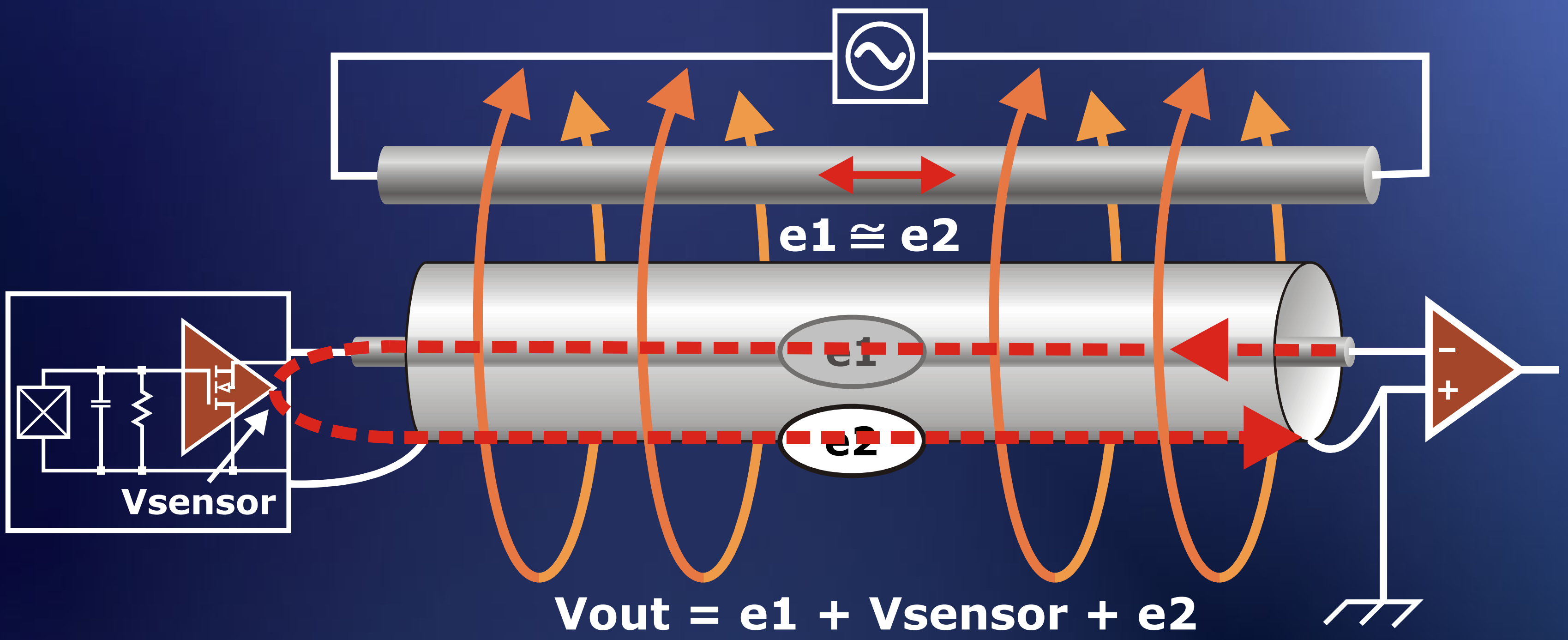
- If this coaxial cable is connecting a floating IEPE accelerometer to an amplifier…

…WHAT WILL HAPPEN?



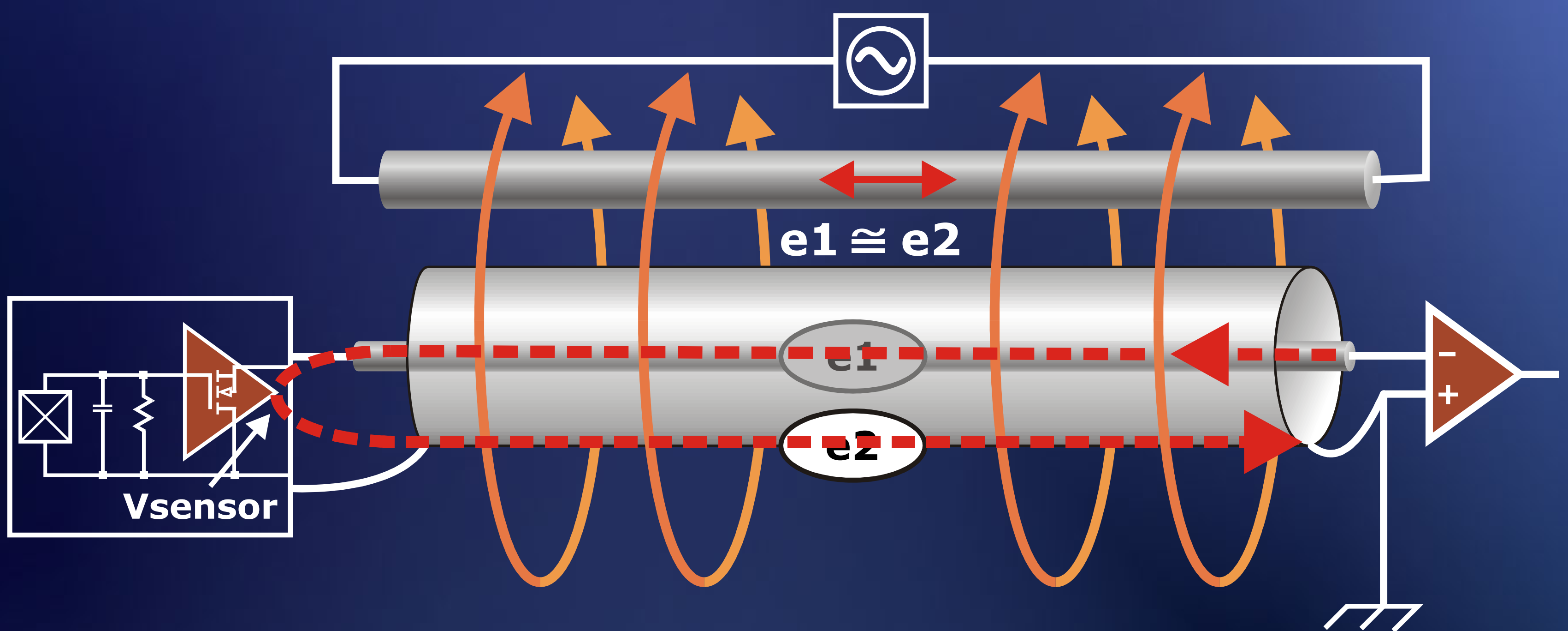
Magnetic Coupling Errors in Measurement Systems

- To answer this we develop a ***loop equation*** as seen by the input circuit of the signal conditioner.



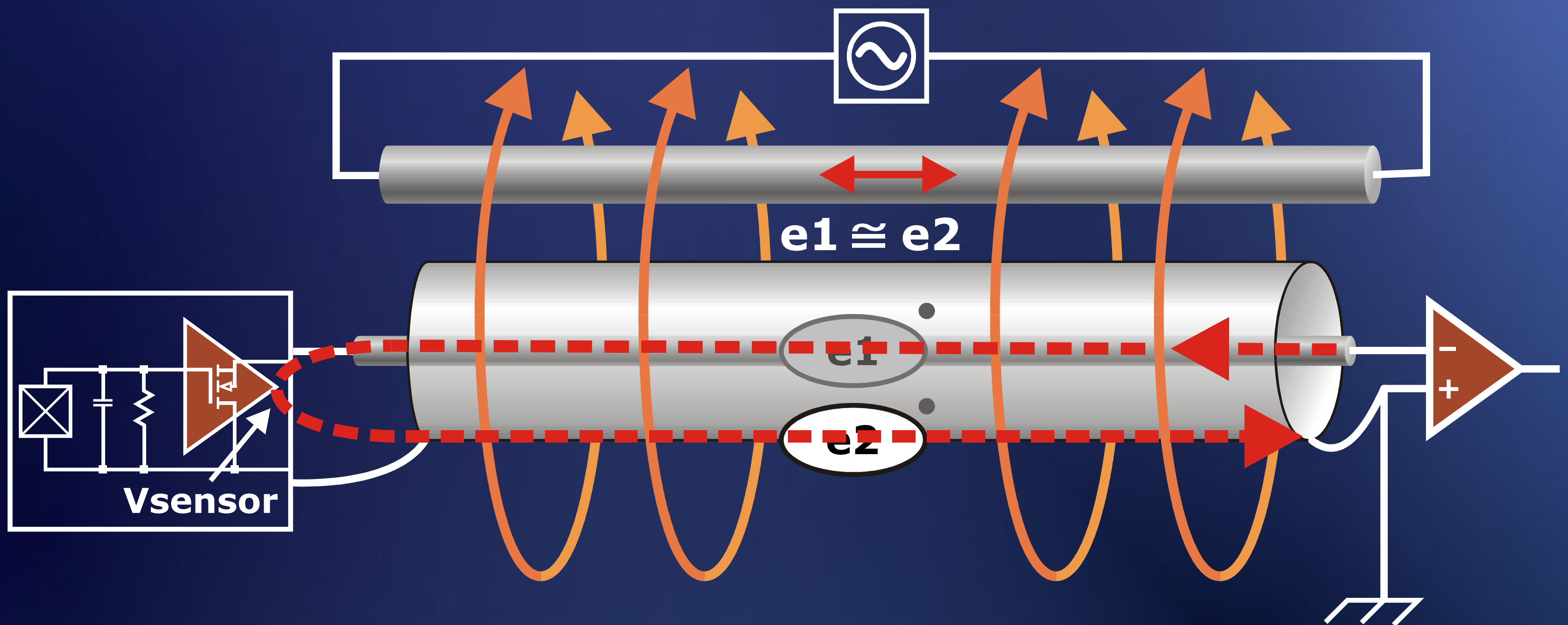
Magnetic Coupling Errors in Measurement Systems

- It is also important to note that the spatial equivalence of conductors within a cable will also cause the induced voltages to be of the same ***phase***.



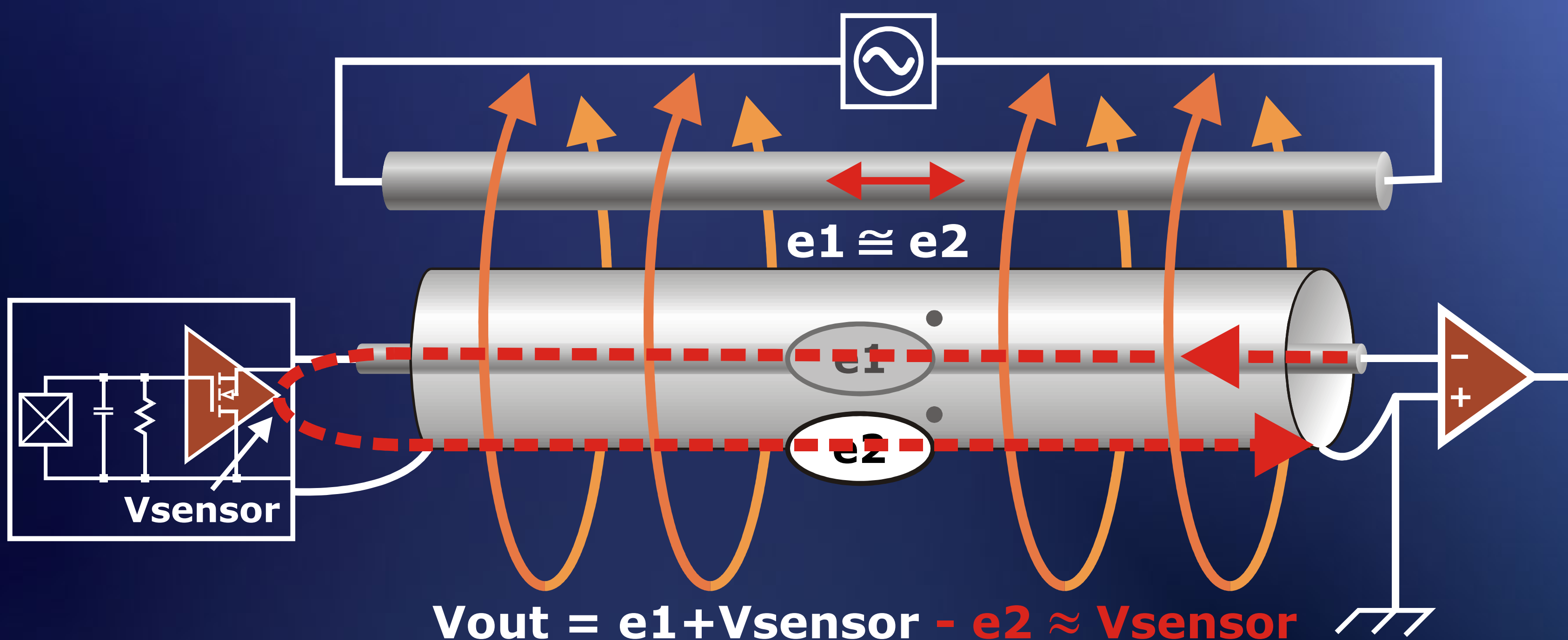
Magnetic Coupling Errors in Measurement Systems

- We borrow from the notations in the field of magnetics and symbolize “in phase” signals with a solid DOT.



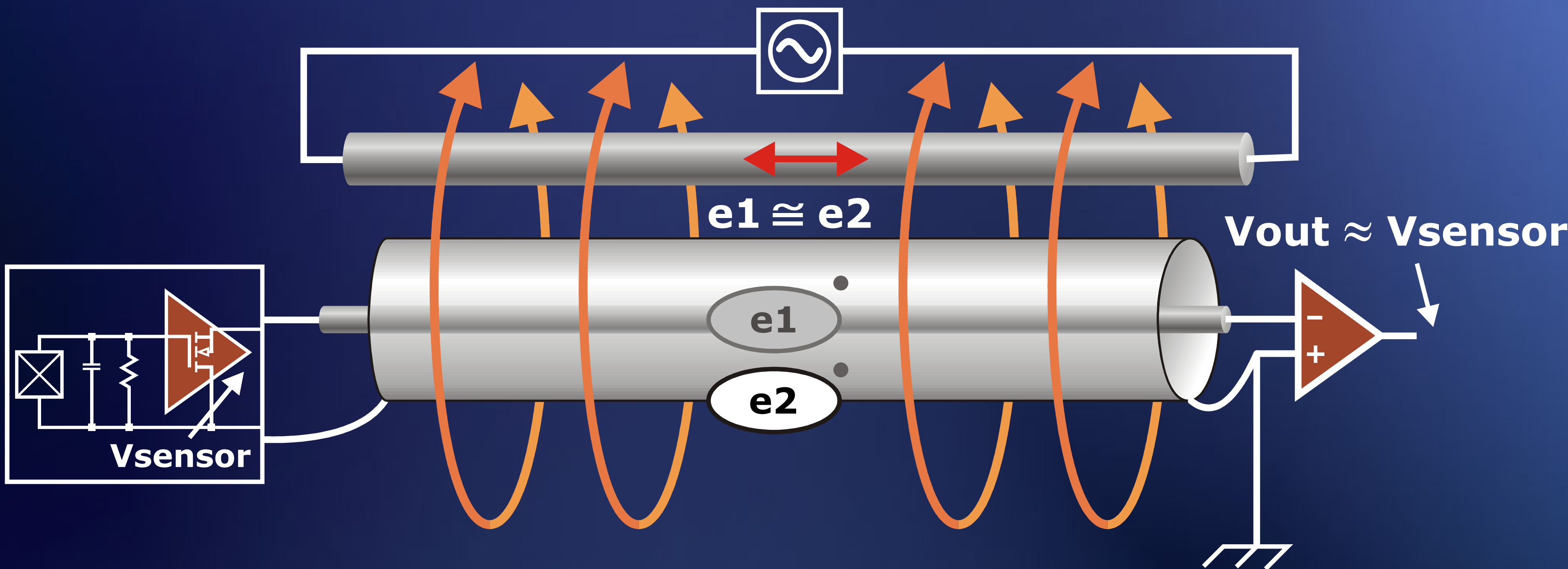
Magnetic Coupling Errors in Measurement Systems

- Since the induced voltages are of equal amplitude and equal phase they will tend to cancel in a loop equation as seen from the input stage of a signal conditioner.



Magnetic Coupling Errors in Measurement Systems

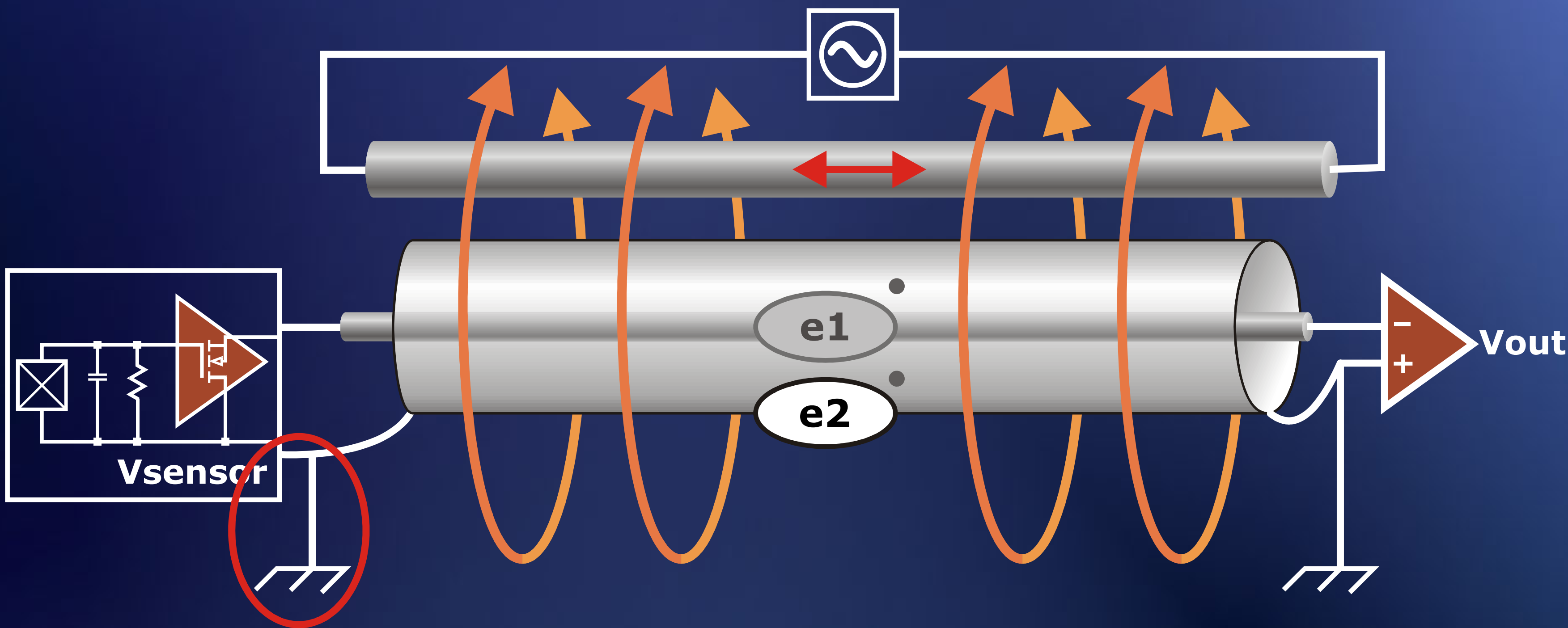
- It can be said that a single-ended connection to a floating sensor is relatively immune to magnetically induced signals if the high and low conductors are spatially equivalent.



The Ground Loop Problem

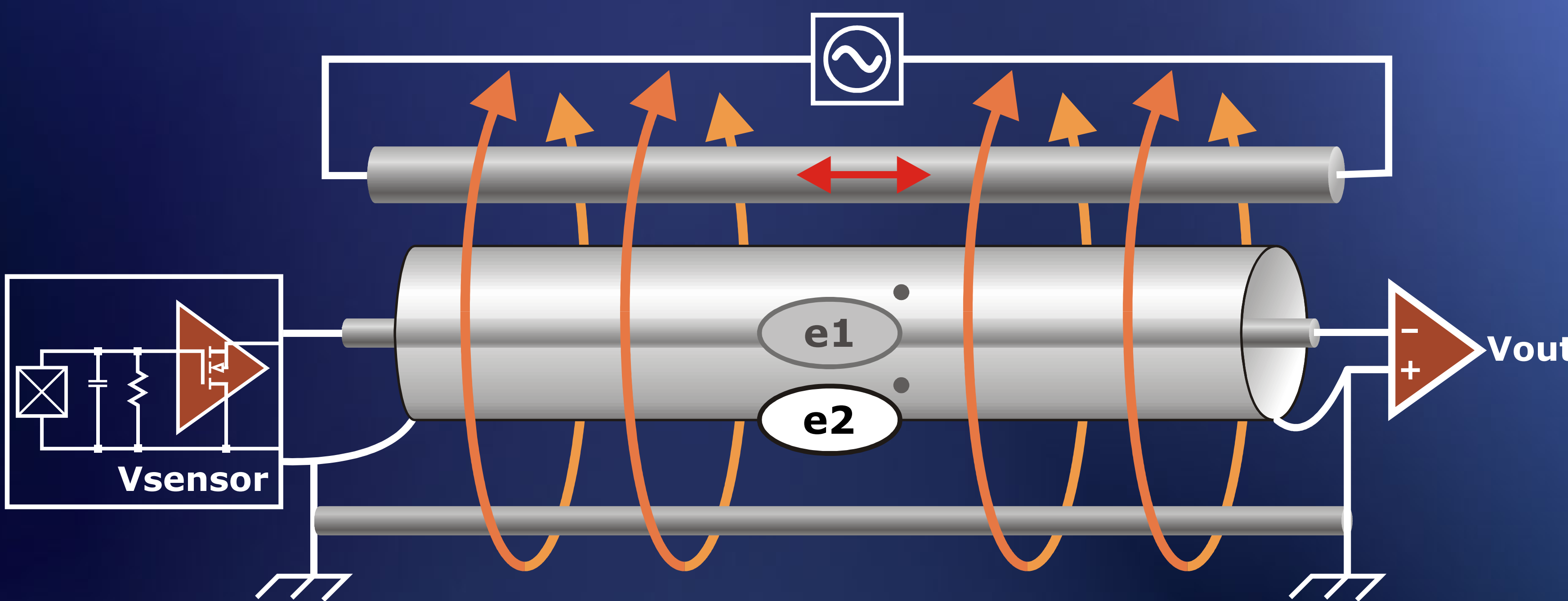
- If however the cable shield is grounded at both ends, we have a new situation!

...The dreaded ***"Ground Loop"***



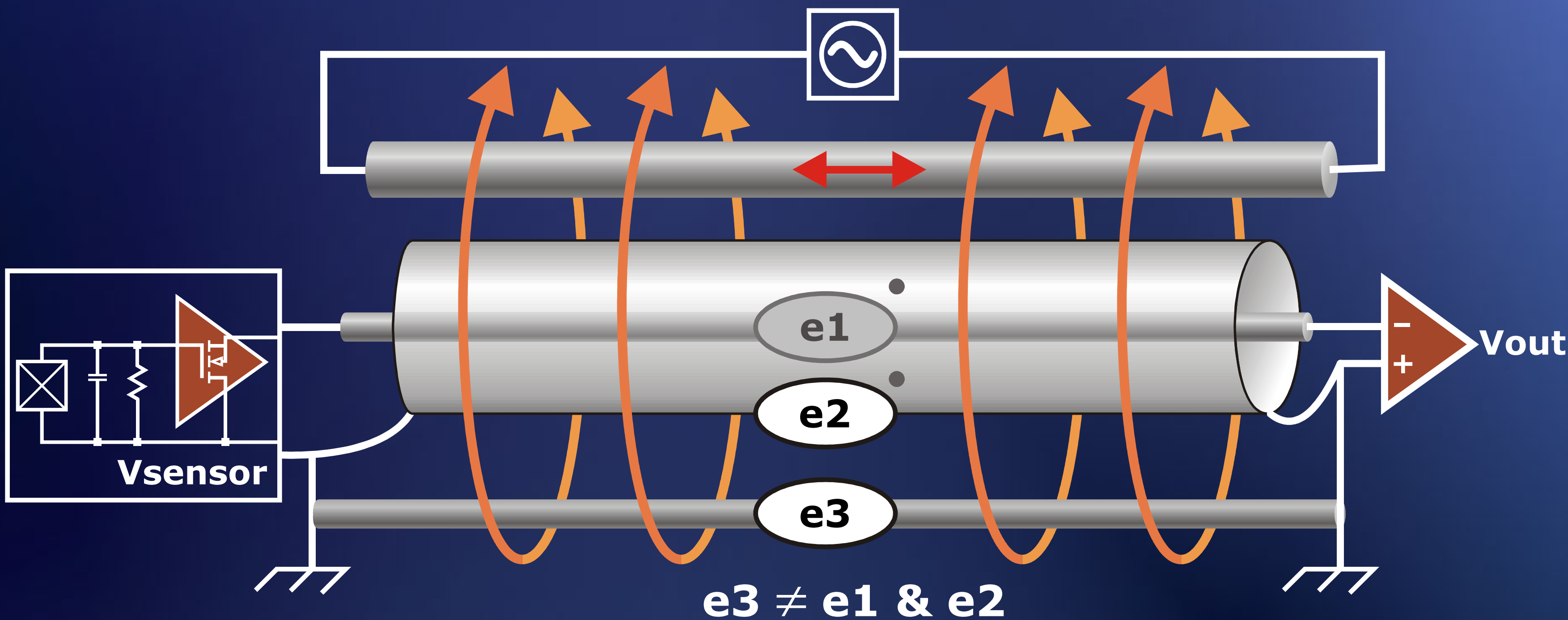
The Ground Loop Problem

- Whether it is a facility green wire ground, common earth ground, or some other hard wired ground connection, there is now a new segment to be analyzed in our cable system.



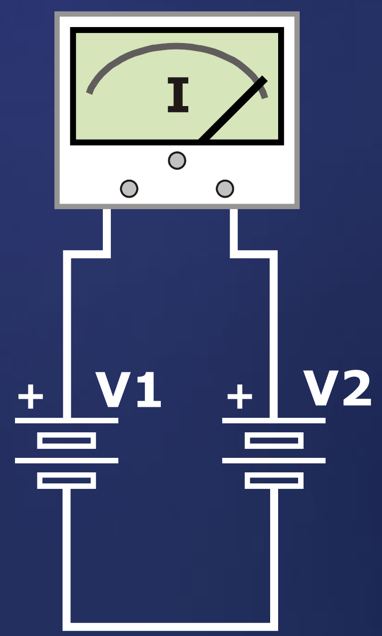
The Ground Loop Problem

- This segment will have it’s own unique induced voltage and most likely this voltage will be very different from that of our cable.



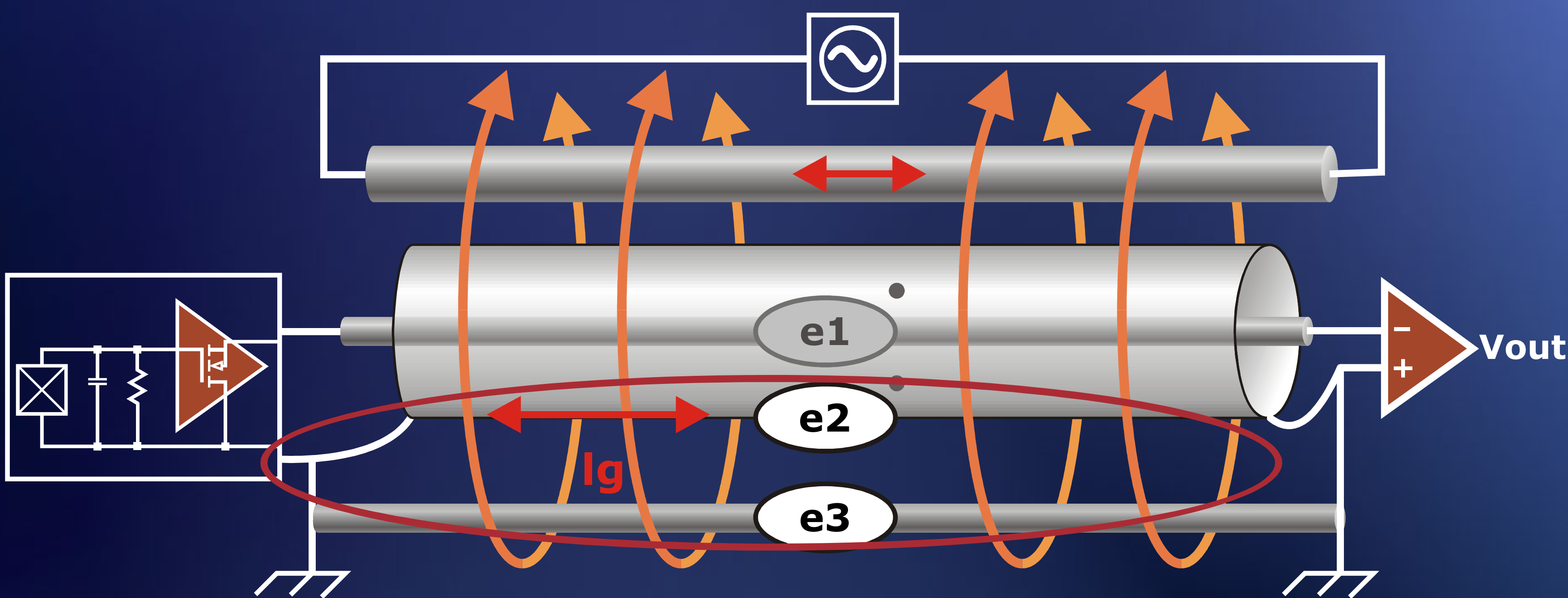
Current Flow in Ground Loop

- We know that very high currents will flow when we connect signal sources together if their voltages are not equal.



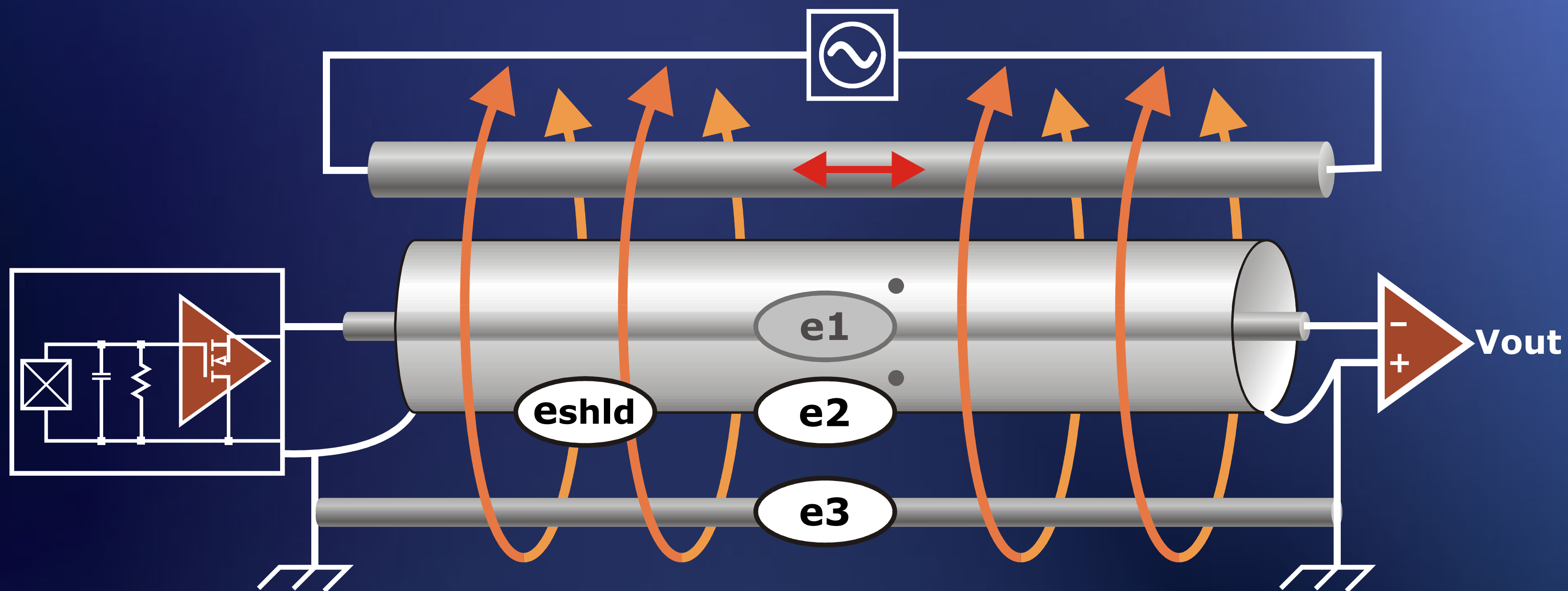
Current Flow in Ground Loop

- Similarly potentially high "loop current" Ig will flow when these differing induced voltages are connected together through the low impedance of the ground loop.



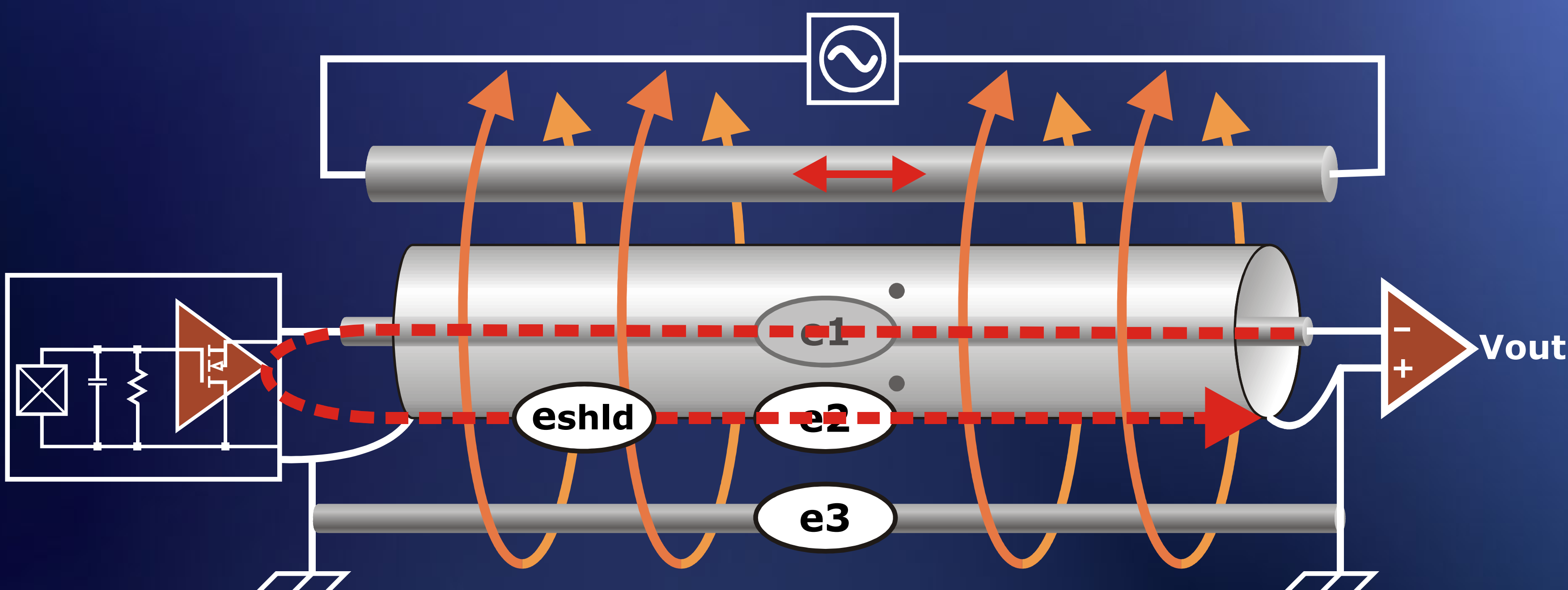
Current Flow in Ground Loop

- This current will create a voltage eshld on the cable shield equal to Ig * Rshld, where Rshld is the end to end resistance of the cable shield.



The Ground Loop Problem

- We see in the new loop equation that eshld is seen at the channel input and will be amplified by any channel gain.



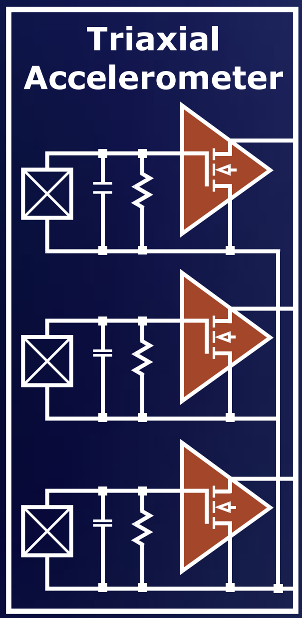
Vout= e1+ Vsensor + eshld- e2 ≈ Vsensor + eshld

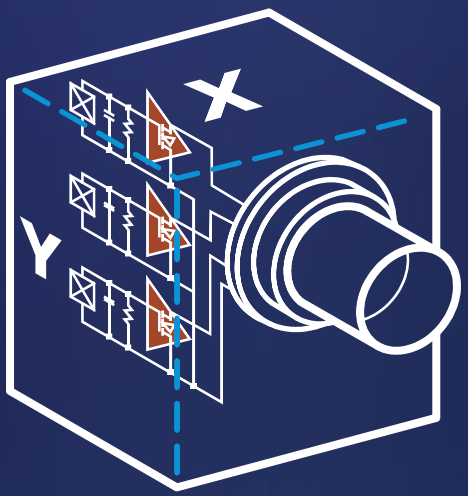
Cabling Difficulties with Triaxial Accelerometers

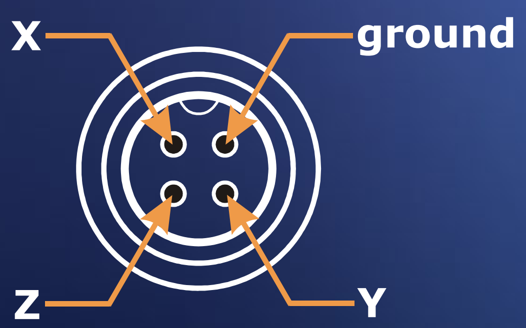
- *Common "Gotcha #1":* Consider the seemingly simple task of connecting a triaxial accelerometer to a distantly located signal conditioning system.

Cabling Difficulties with Triaxial Accelerometers

- The triaxial accelerometer employs three separate IEPE buffer circuits, each sharing a common return. In order to minimize sensor size and mass, a miniature 4-pin connector is often used. The connector contains the signal output of each of the X, Y and Z accelerometers and a common return that is usually connected to the sensor case.

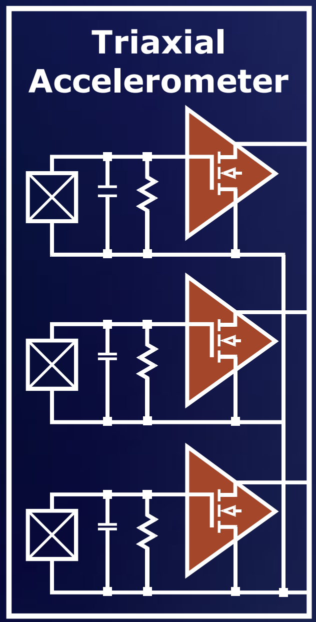




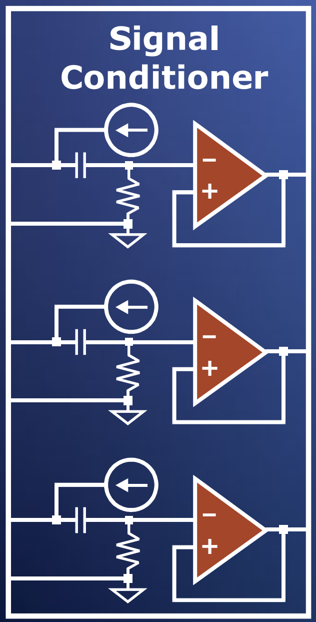


Cabling Difficulties with Triaxial Accelerometers

- How do we properly connect the three accelerometer channels to three channels of DISTANT signal conditioning?

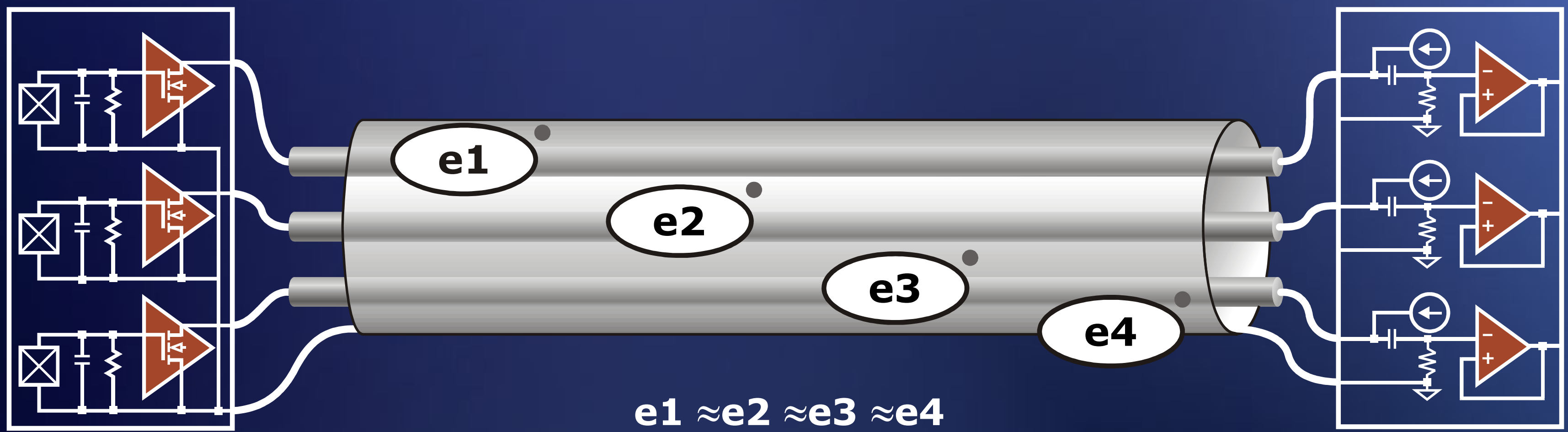


?



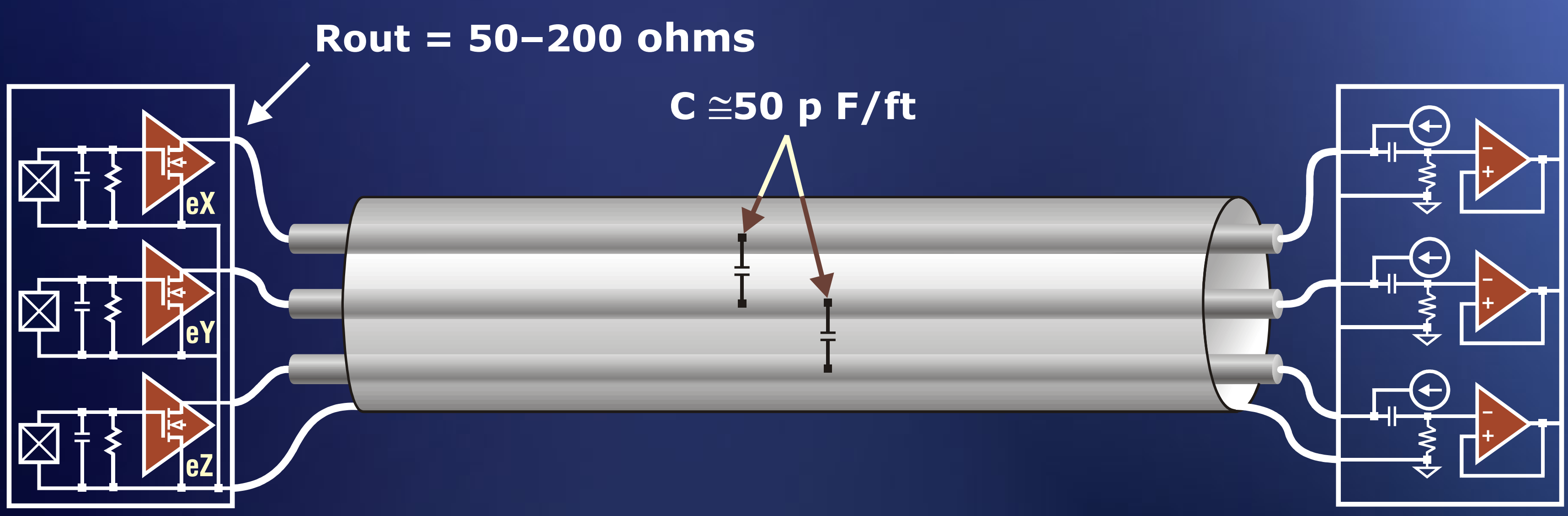
Cabling Difficulties with Triaxial Accelerometers

- One cabling option that performs well for very short cable runs is to bundle all three signal carrying wires in a single “shielded triplet” cable as shown below.



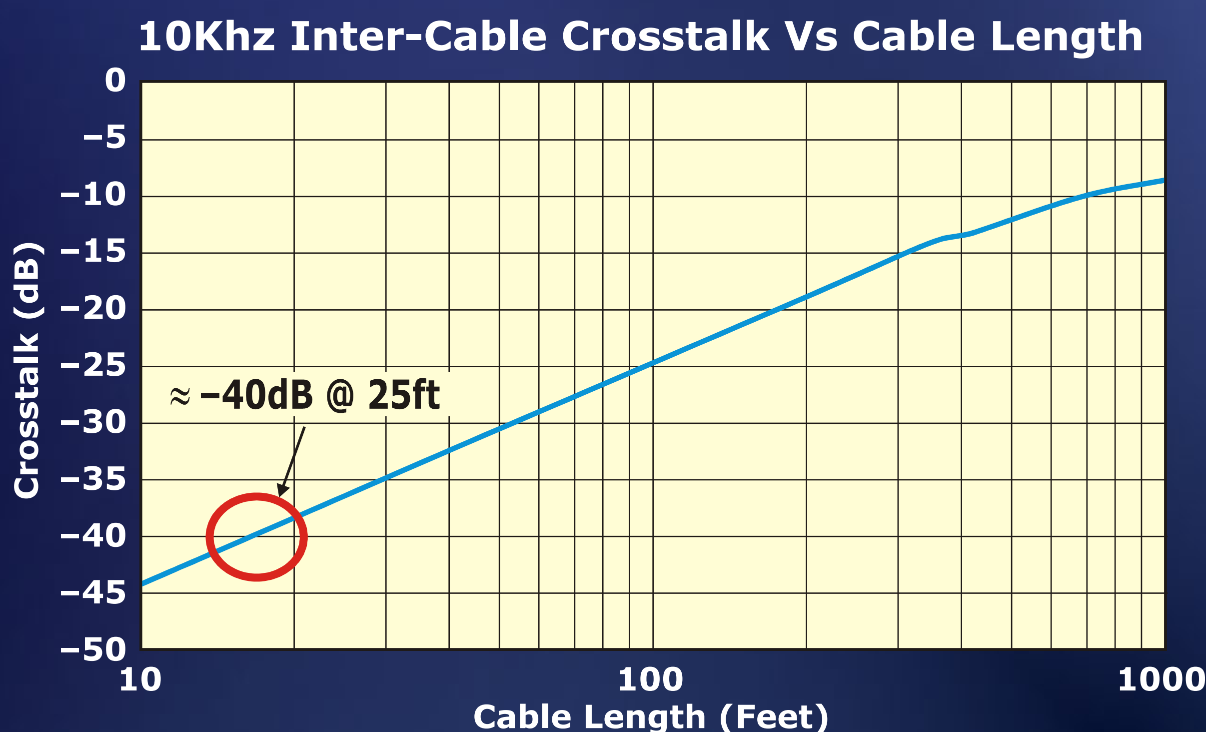
Cabling Difficulties with Triaxial Accelerometers

- This cabling scheme is only useful for very short cable runs where capacitive coupling between the signal conductors (crosstalk) is within acceptable levels.



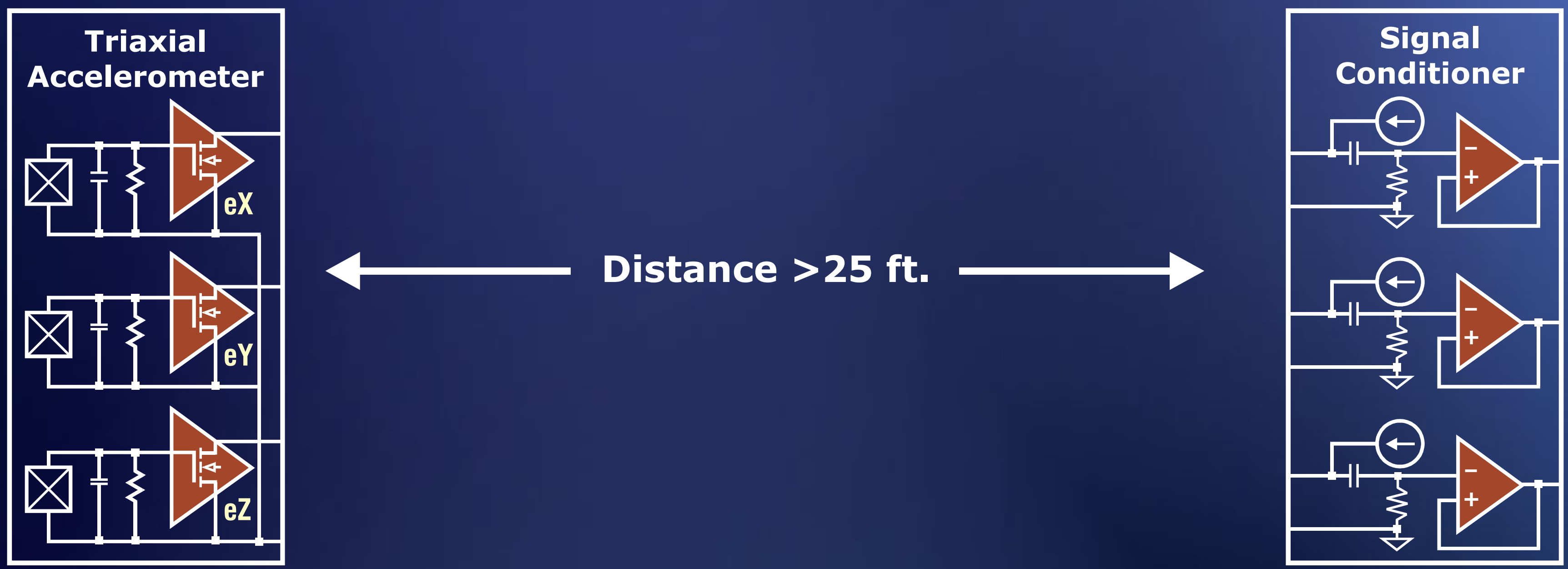
Cabling Difficulties with Triaxial Accelerometers

- If we assume the IEPE accelerometer has 200 ohms of output impedance, and the cable has 50pF/ft of conductor to conductor capacitance, then we can calculate the following crosstalk:



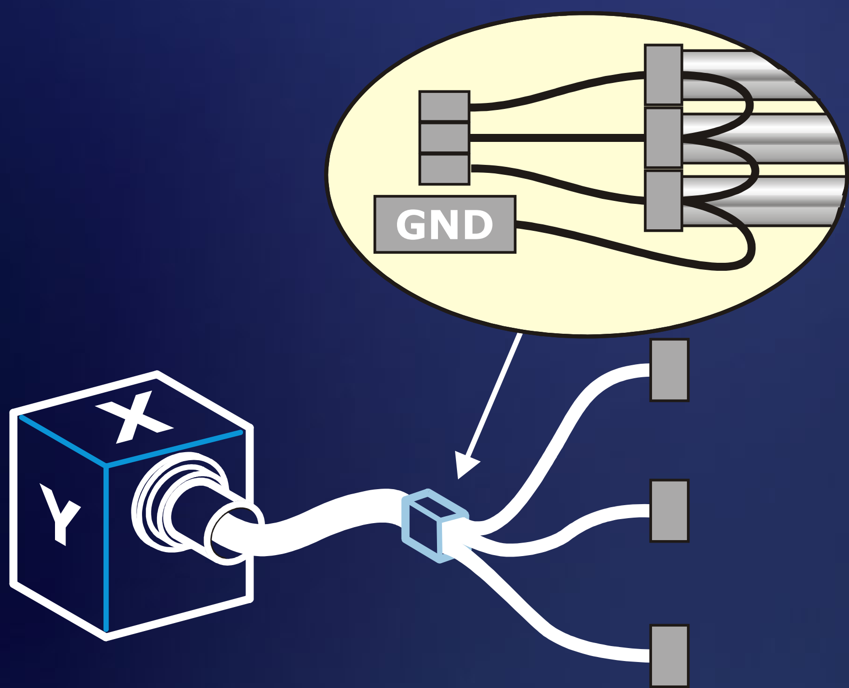
Cabling Difficulties with Triaxial Accelerometers

- We emphasize that this discussion considers the case of a long interconnecting cable, where it is important to provide shielding of the inner conductors.

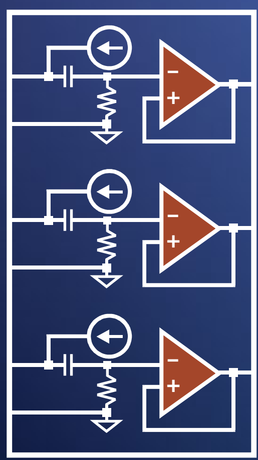


Cabling Difficulties with Triaxial Accelerometers

- We may start with a manufacturer supplied Breakout cable which conveniently breaks out the four sensor pins to three coaxial cables with BNC connectors.

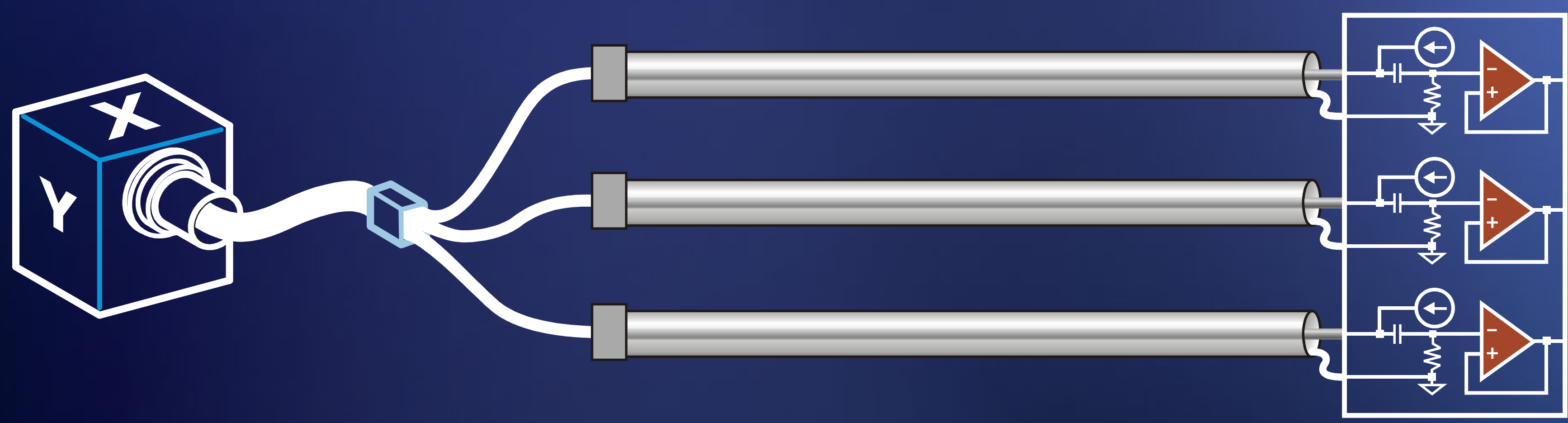


Note: The shields of each coaxial cable are tied together in the breakout cable



Cabling Difficulties with Triaxial Accelerometers

- We might then use BNC cables to connect to the signal conditioner inputs.



Cabling Difficulties with Triaxial Accelerometers

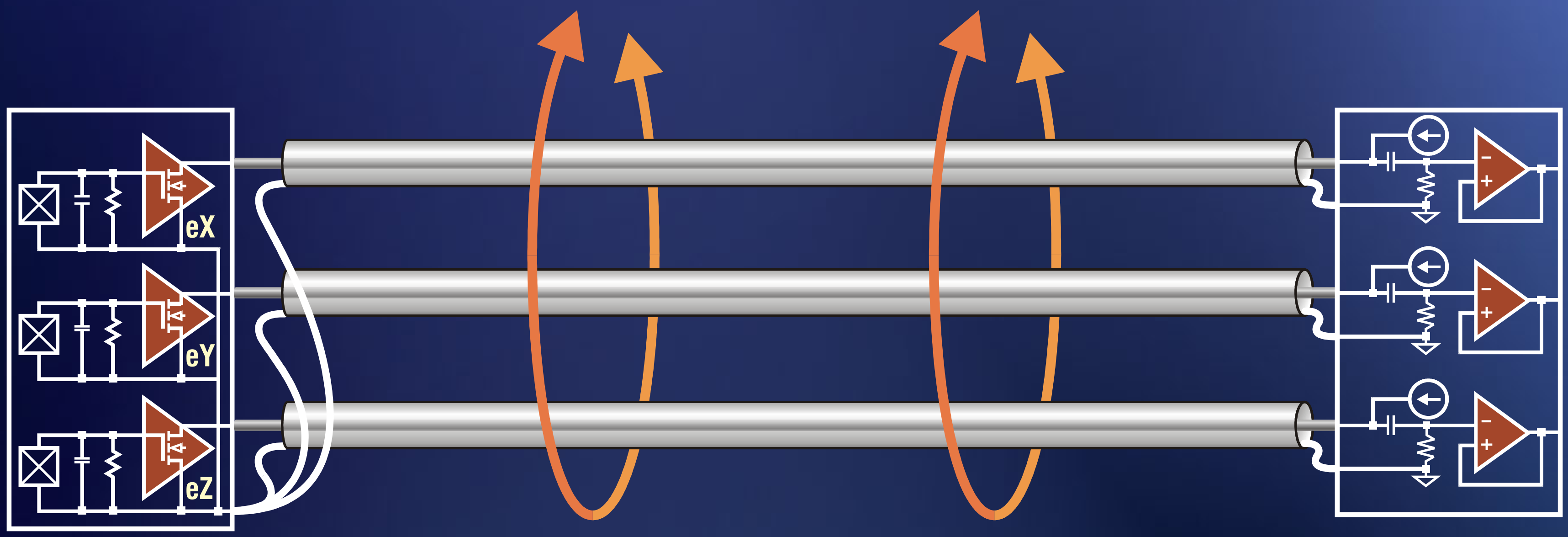
- This shows the resulting connections to the IEPE circuits.

Cabling Difficulties with Triaxial Accelerometers

- It is important to note that traditional IEPE signal conditioners utilize a single-ended input scheme, whereby input “low” is connected to ground at each signal conditioner input. This is usually an appropriate connection since it provides a solid ground connection to the shield of the coaxial cable.

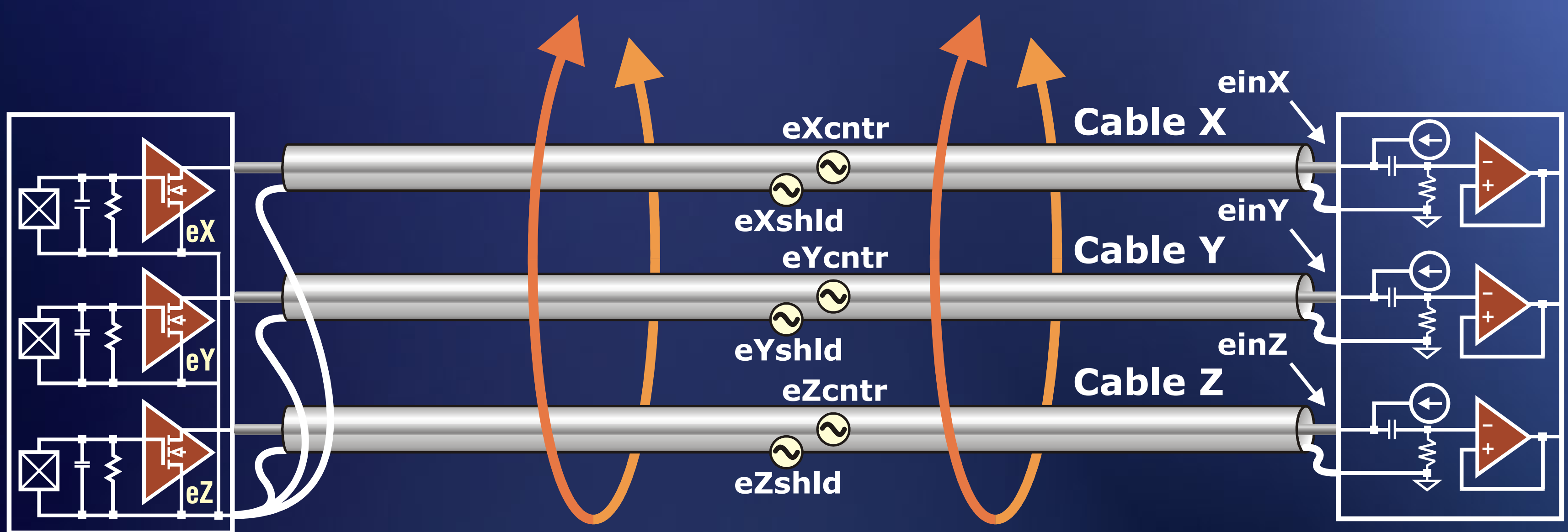
Cabling Difficulties with Triaxial Accelerometers

- We wish to determine how this connection scheme would perform in the presence of high magnetic fields?



Cabling Difficulties with Triaxial Accelerometers

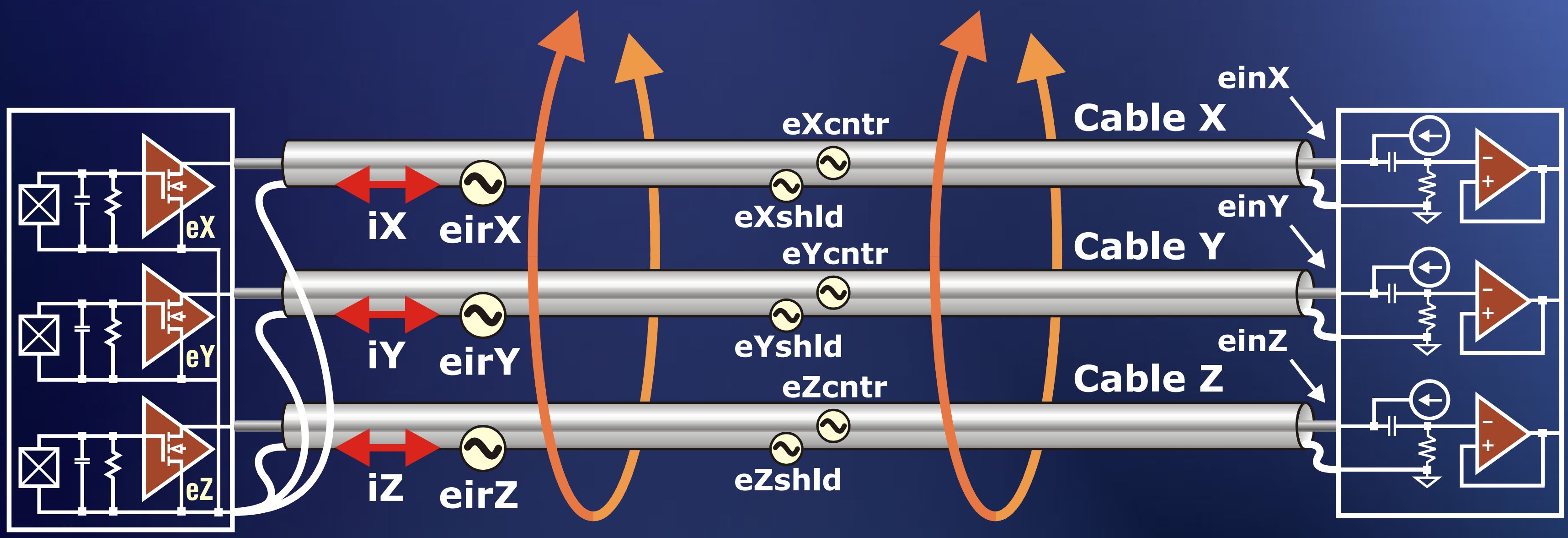
- ***Step 1:*** We begin by inserting induced voltage sources in each conductive segment.



Cabling Difficulties with Triaxial Accelerometers

- ***Step 2:*** Determine whether there is current flow in the cable shield and an associated cable shield IR drop.

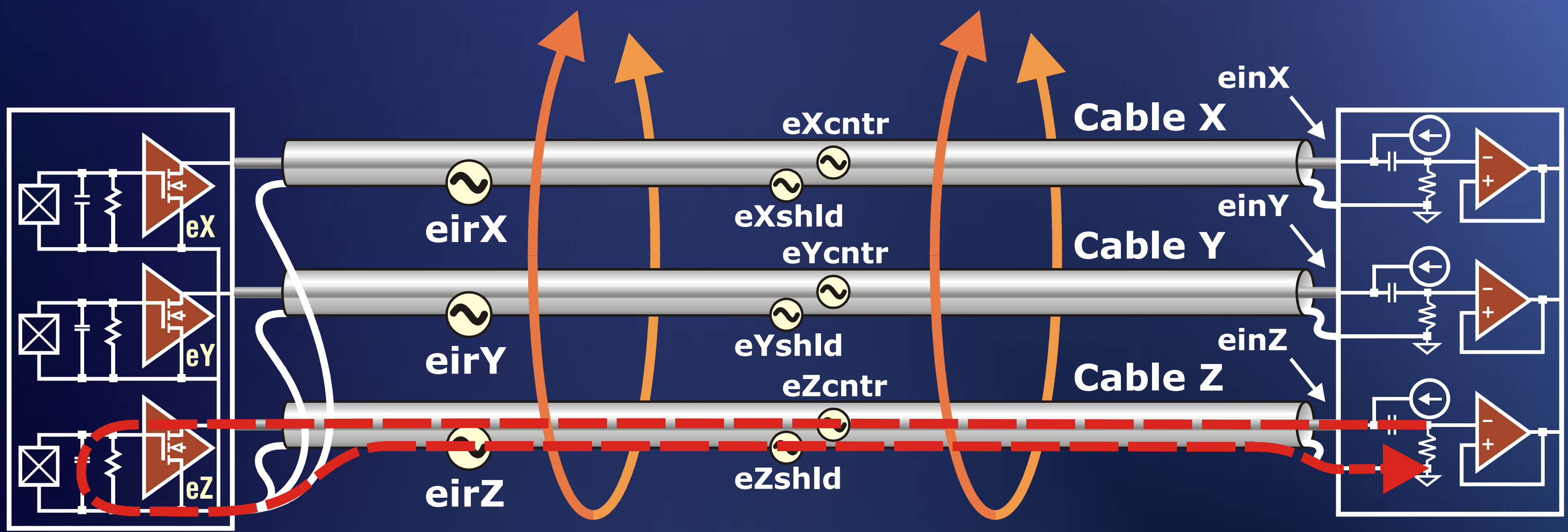
In this cable scheme…*YES!*



Cabling Difficulties with Triaxial Accelerometers

- ***Step 3:*** We then draw the loop equation for each channel input.

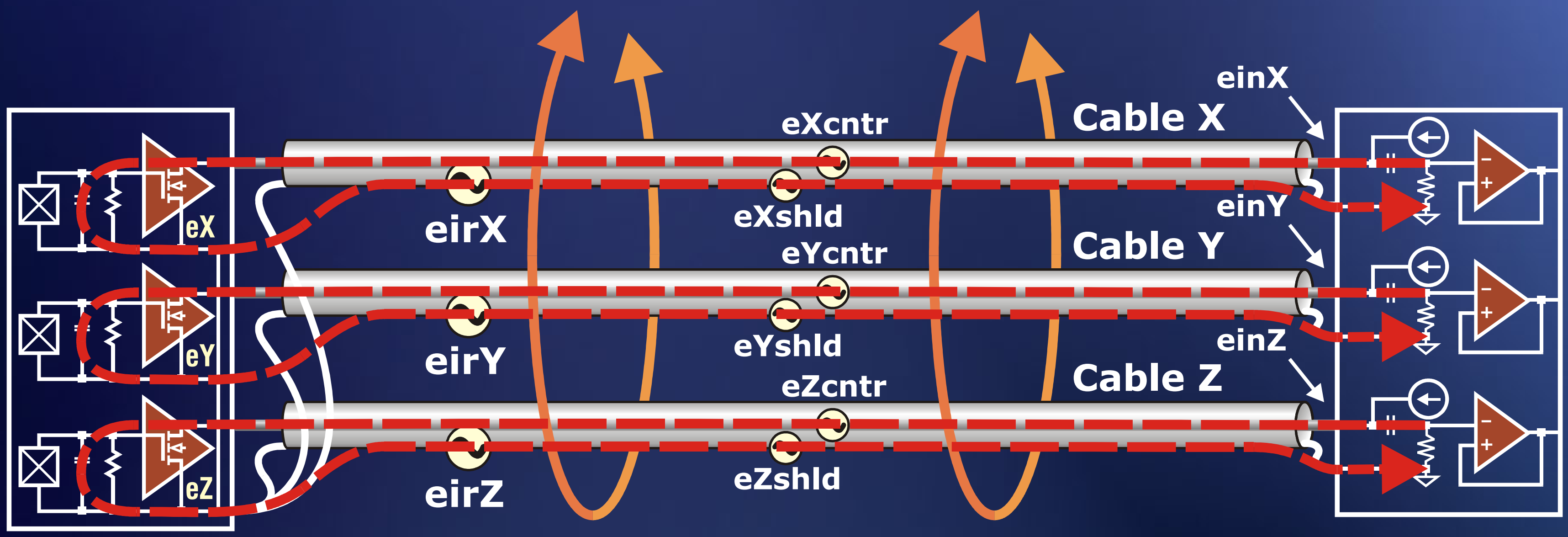
  We see that there is an induced noise signal eirZ which will appear at the input and is amplified by any channel gain.



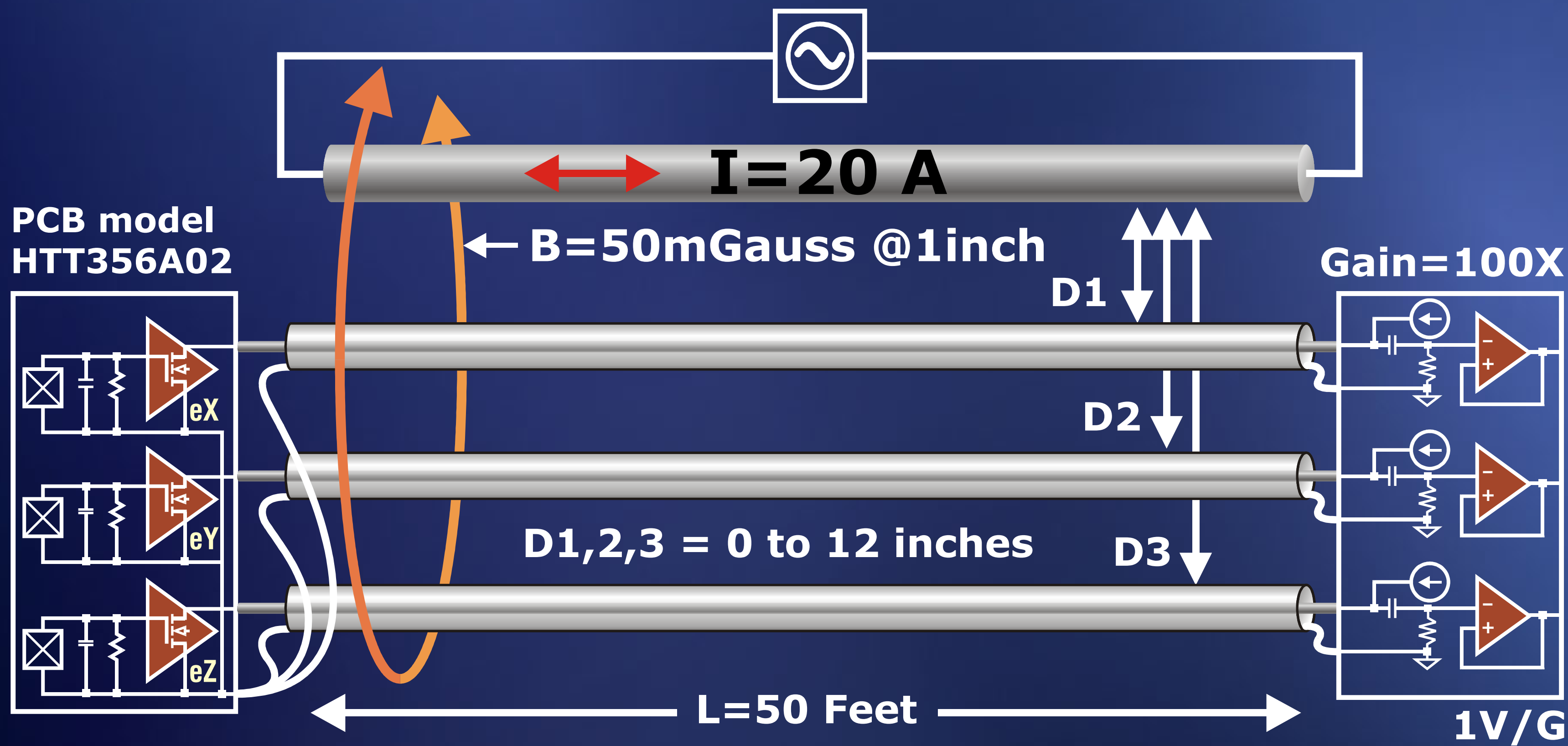
einZ = eZcntr + eZ + eirZ – eZshld = eZ + eirZ

Cabling Difficulties with Triaxial Accelerometers

- Similarly each loop equation includes an error caused by IR drop in the cable shield.



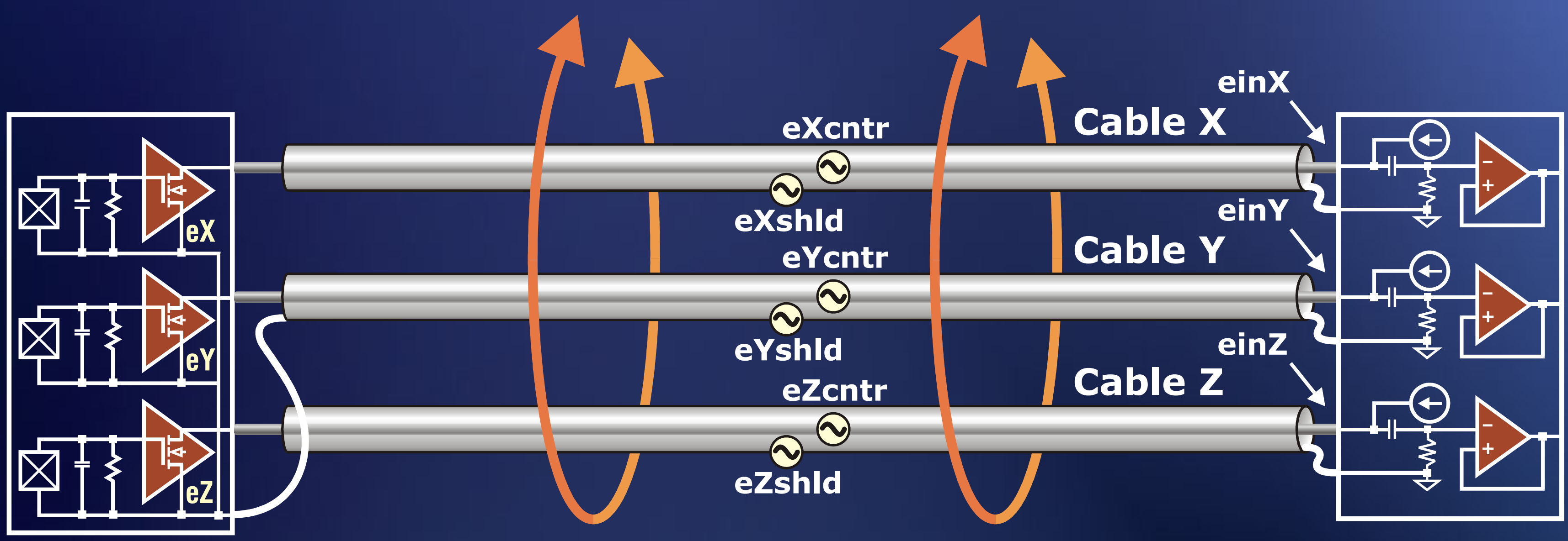
Experimental Result Test #1



	RMS reading	dB re Full Scale	Equivalent G's peak
Chan X	12 mVRMS	-55	0.017
Chan Y	4 mVRMS	-65	0.006
Chan Z	14 mVRMS	-54	0.020

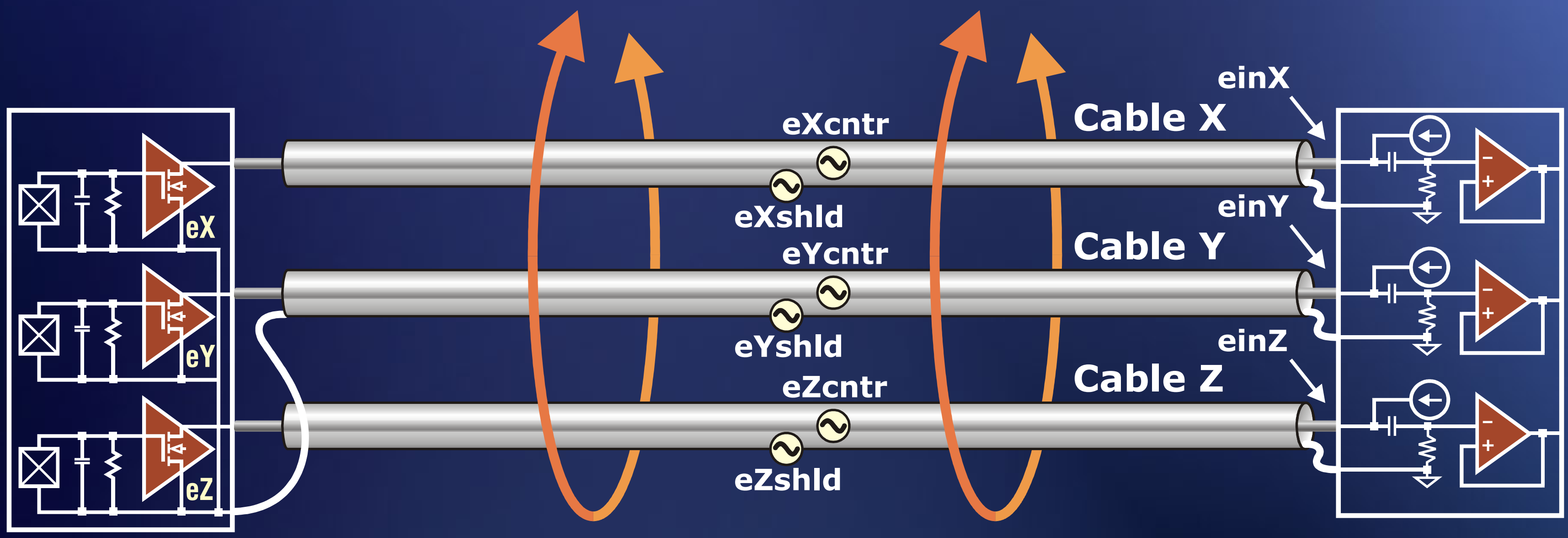
Cabling Difficulties with Triaxial Accelerometers

- One solution often employed to solve this problem is to simply break the loops by disconnecting two of the three cable shields at the sensor side of the cable connection.



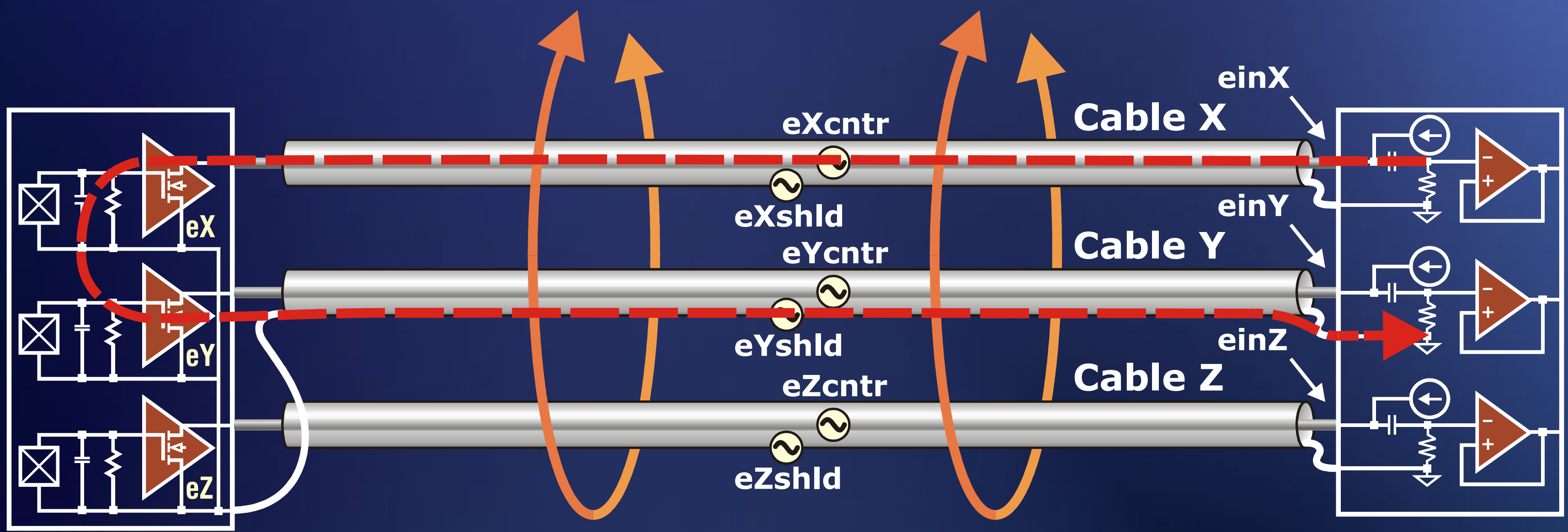
Cabling Difficulties with Triaxial Accelerometers

- This does indeed prevent current flow in the cable shields, and the second induced cable shield error voltage, however a new problem is introduced.



Cabling Difficulties with Triaxial Accelerometers

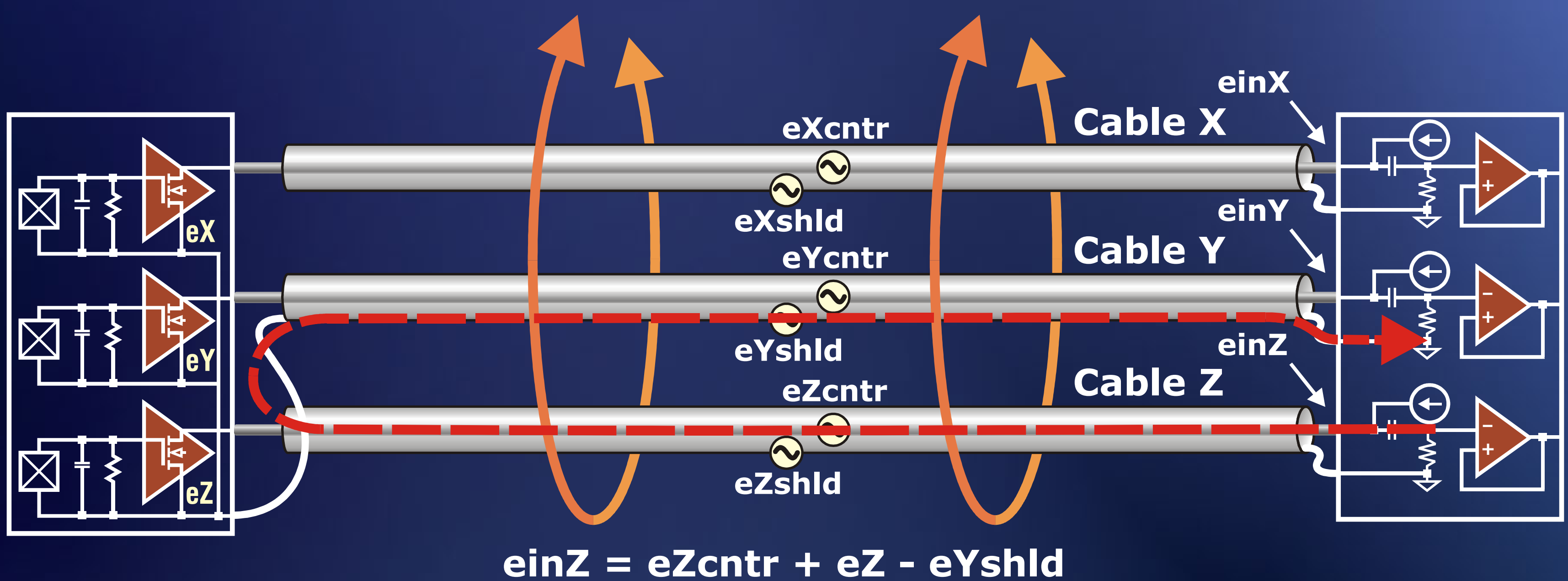
- We can see below that the loop equation for einX now involves shield noise of cable Y and the center conductor noise of cable X. Since these are different cables, they will likely have different induced signal amplitudes and may NOT fully cancel.



einX= eXcntr + eX - eYshld

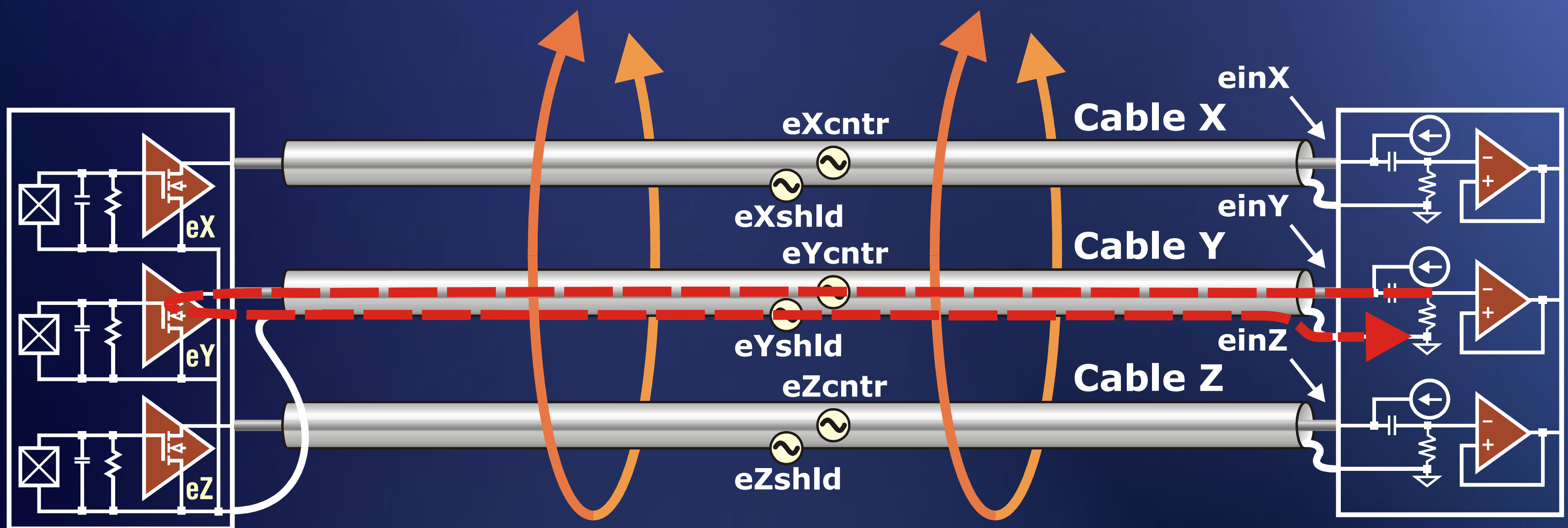
Cabling Difficulties with Triaxial Accelerometers

- Similarly, a noise signal at einZ will contain the center conductor noise of cable Z and the shield noise of cable Y, and again these may not fully cancel.



Cabling Difficulties with Triaxial Accelerometers

- We notice that the loop equation for einY contains center conductor and shield noise of cable Y and since these are of the same cable, we would expect these to more fully cancel.



$$einY = eYcntr + eY - eYshld \cong eY$$

Experimental Result Test#2

Test Data:

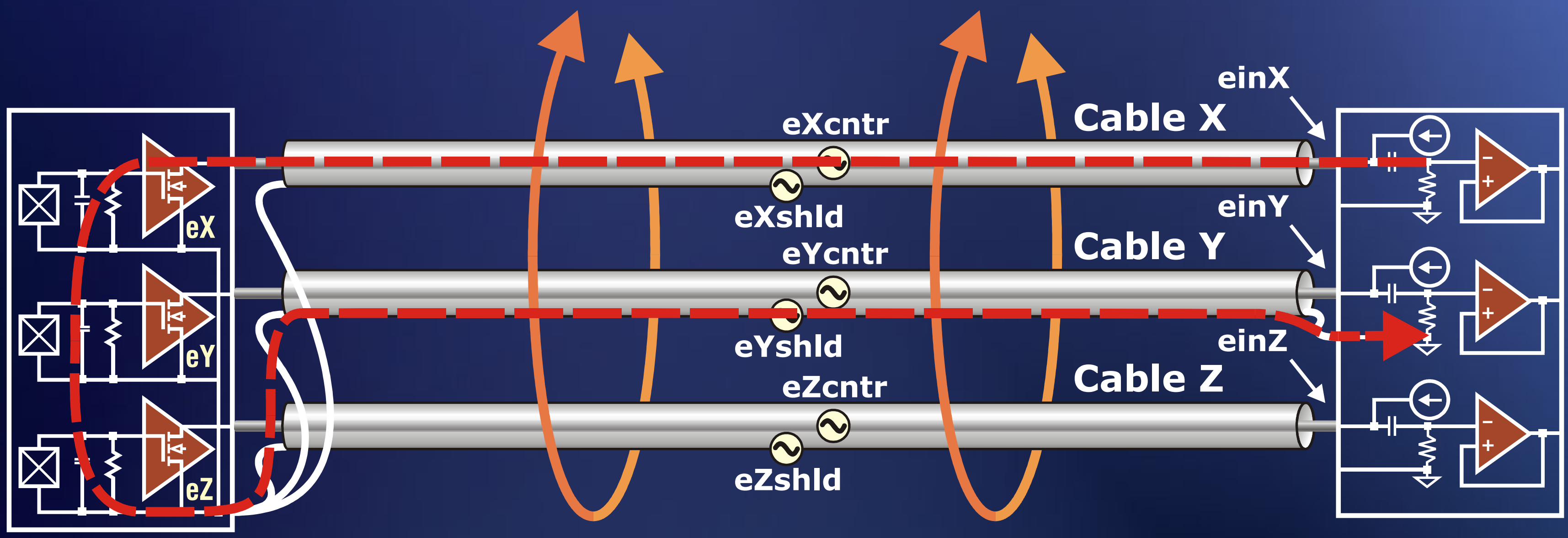
This configuration was simulated by disconnecting the ground connection from the X channel and Z channel coaxial cables at the accelerometer side, i.e., only the Y channel ground is connected through to the accelerometer common return connection

	RMS reading	dB re Full Scale	Equivalent G's peak
Chan X	**11mVRMS**	**-56**	**0.016**
Chan Y	**0.2mVRMS**	**-91**	**0.0002**
Chan Z	**16mVRMS**	**-53**	**0.022**

As predicted by the above model, a noise signal was present on channel X and Z even though there were NO ground loops. Also as predicted, channel Y was relatively noise free.

Cabling Difficulties with Triaxial Accelerometers

- Breaking the ground loops at the signal conditioner side does not change matters, again we see with any ground return from a different cable the loop equations do not fully cancel and error signals are present in our data.



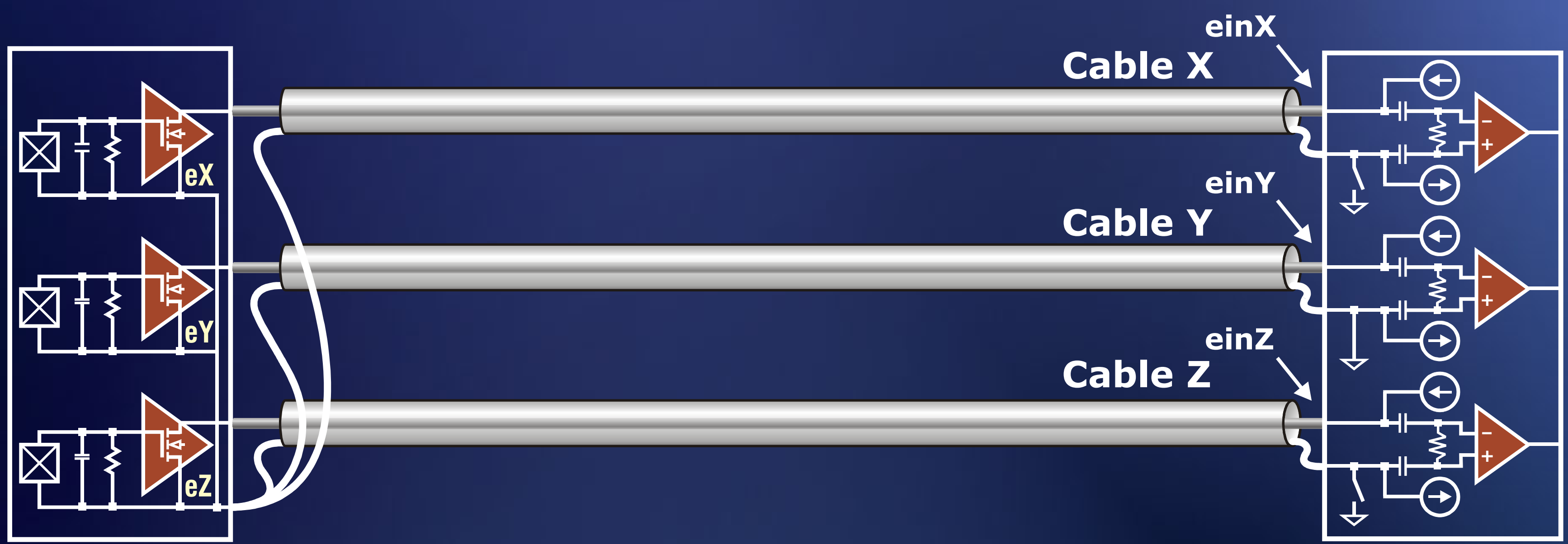
Cabling Difficulties with Triaxial Accelerometers

- After analyzing all possible cabling schemes, it becomes apparent that there is NO cabling scheme to a 4-pin triaxial accelerometer which offers immunity from magnetic interference if the signal conditioner inputs have grounded low inputs.

Then what do we do?

Optimal Signal Conditioner

- For a long distance, cabled connection to triaxial accelerometers, the signal conditioner must have isolated inputs...

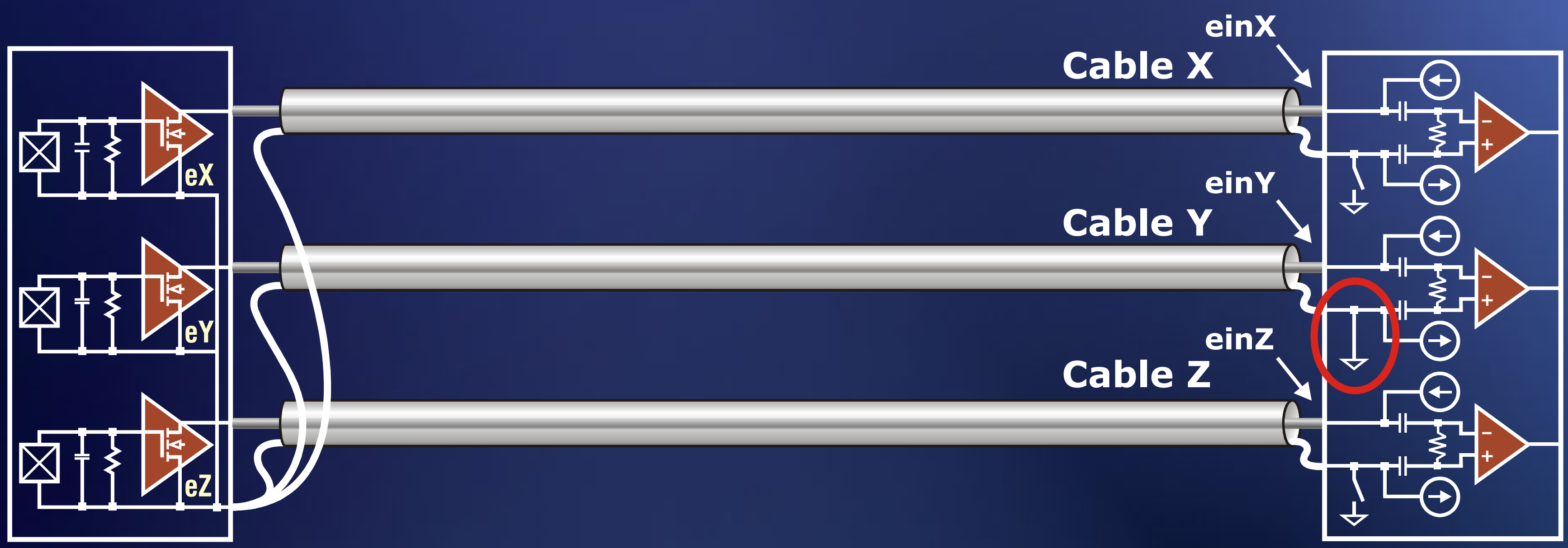


Optimal Signal Conditioner

- ***...and*** each channel must be individually programmable to "grounded" or "isolated" mode.

Optimal Signal Conditioner

- For triaxial accelerometers it is important to ground one channel ***and one channel only*** on each triaxial accelerometer.

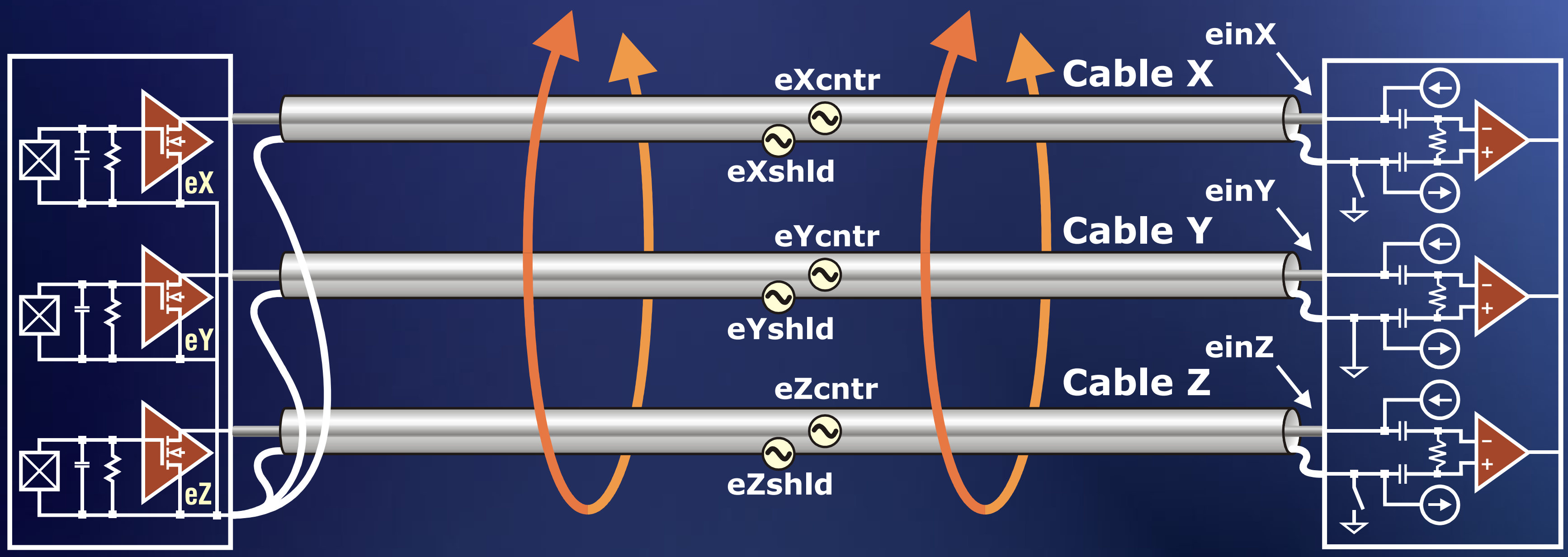


Optimal Signal Conditioner

- This single ground connection provides the electrostatic shield ground for all cables and the accelerometer case.

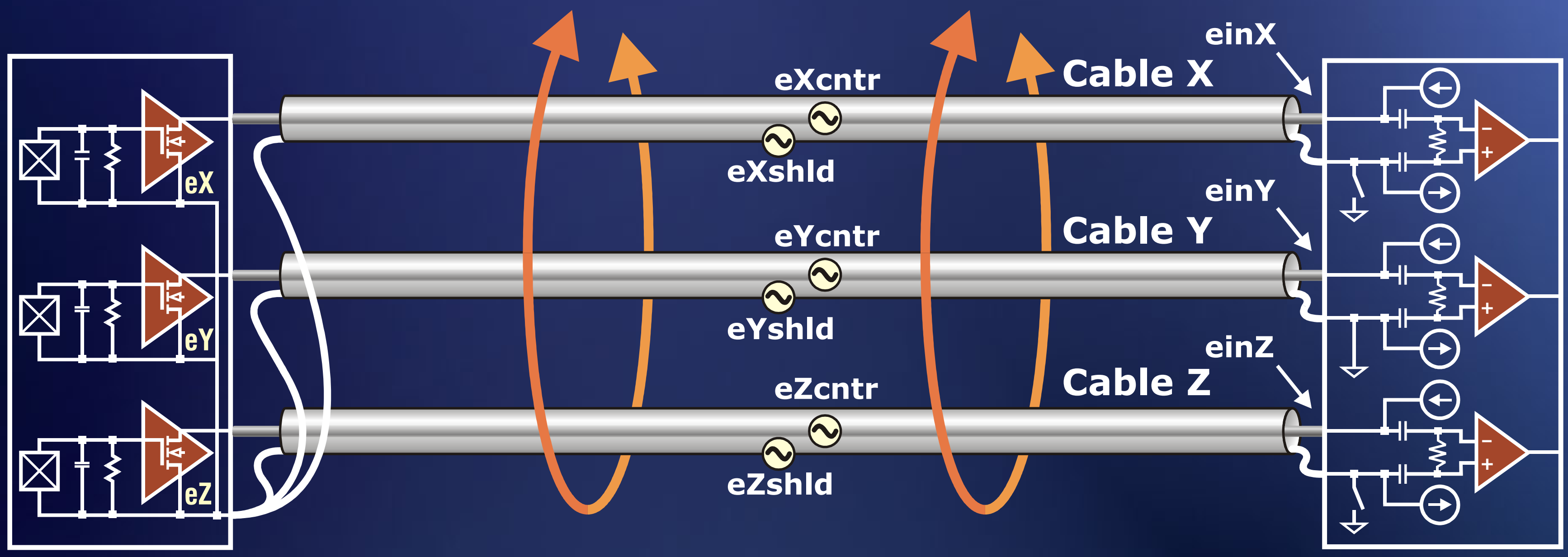
Optimal Signal Conditioner

- We wish to determine how this cabling scheme would perform in a high magnetic field environment.



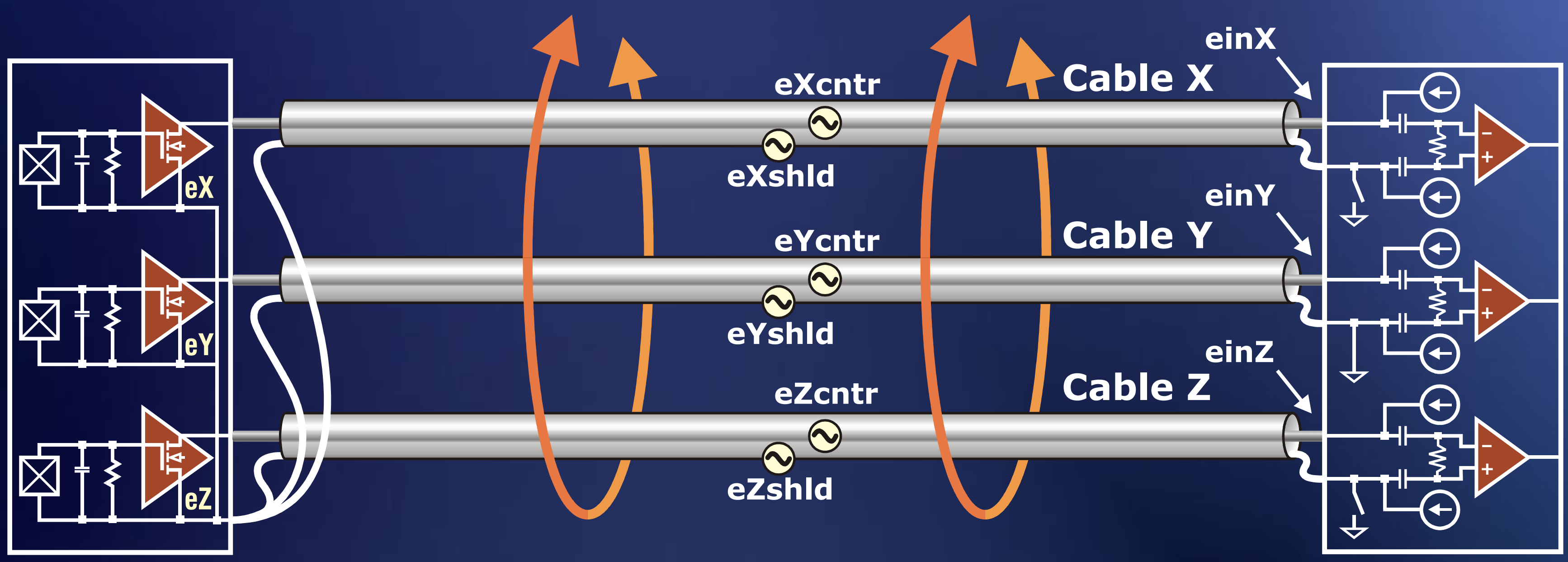
Optimal Signal Conditioner

- **Step 1:** We start by drawing in the induced segment voltages.



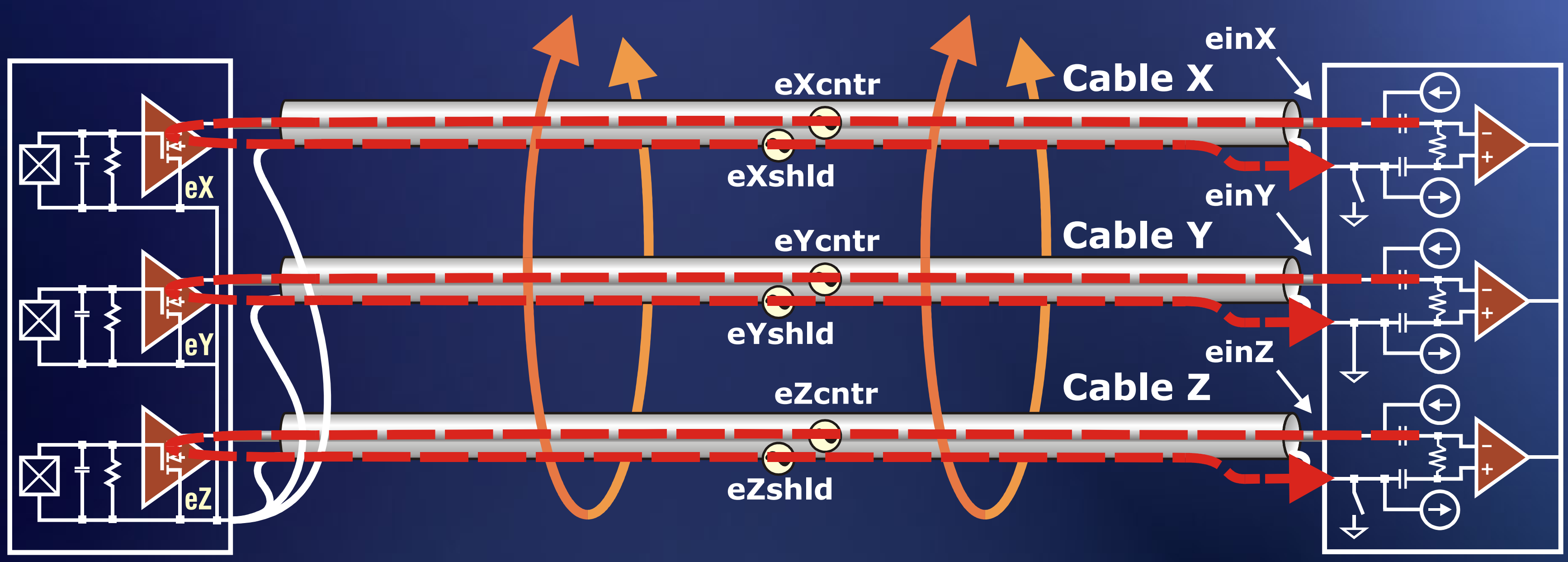
Optimal Signal Conditioner

- **Step 2:** Since only one of the shields is connected to ground at the signal conditioner inputs, we do not have loops in the cable shield connections and therefore no I*R induced signals in the cable shield.



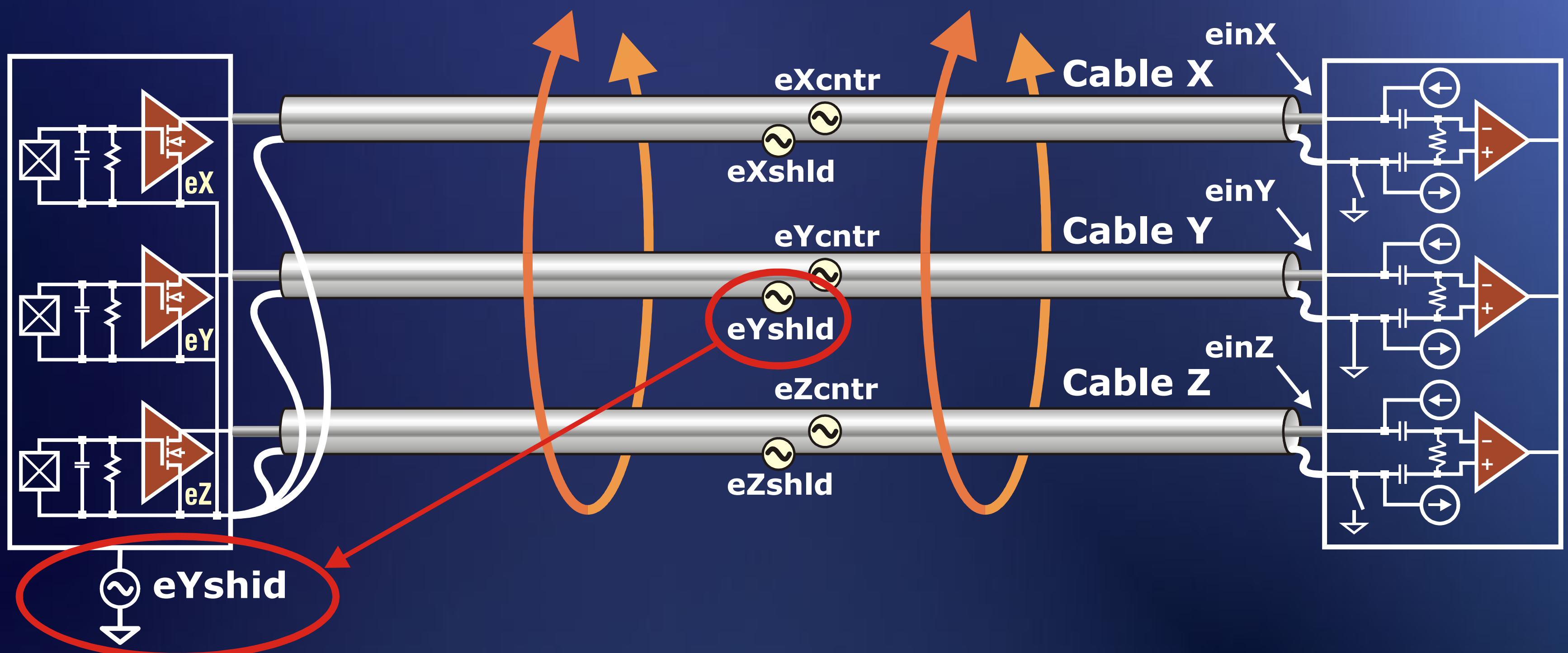
Optimal Signal Conditioner

- **Step 3:** The isolated input structure causes the loop equations for each channel to include the shield noise and center conductor noise of the SAME cable.



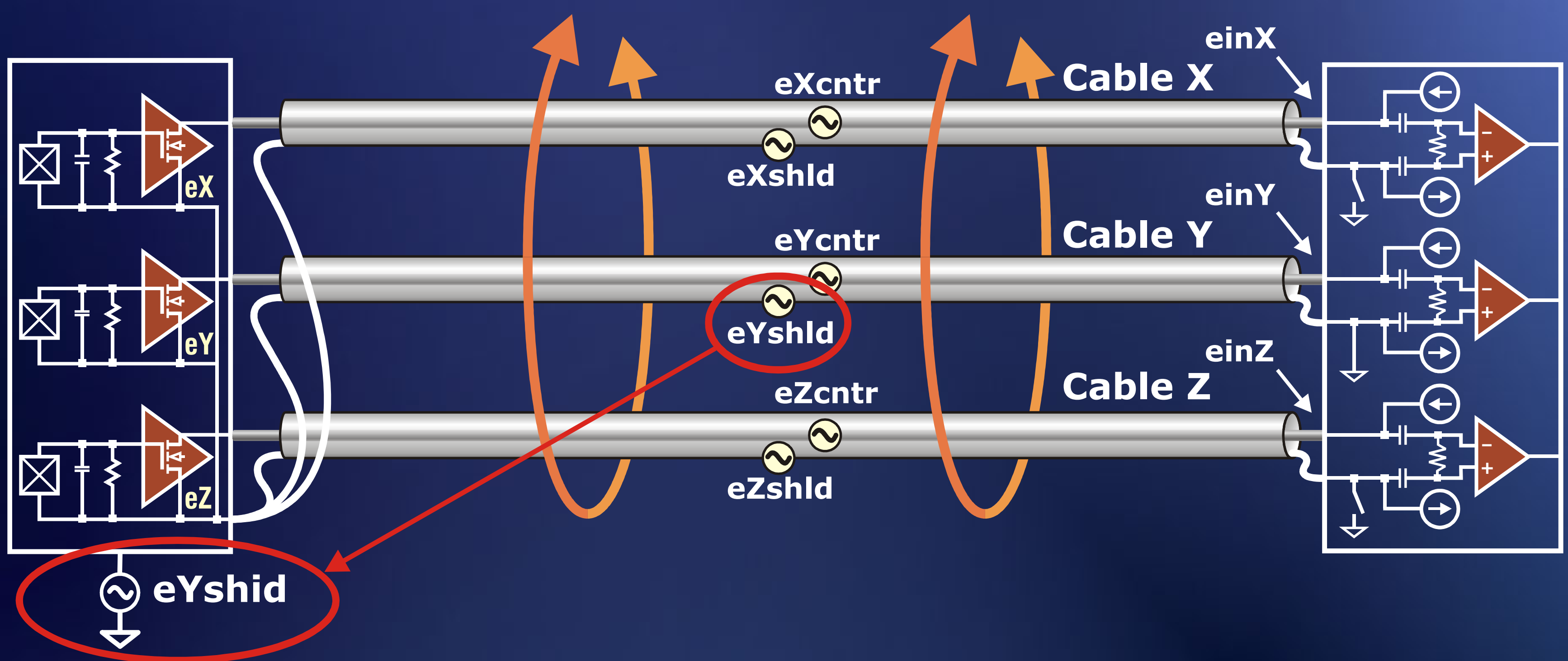
Optimal Signal Conditioner

- We note that since channel Y's cable shield is connected to ground at the signal conditioner, this will force cable noise eYshld to exist at the common connection at the accelerometer case.



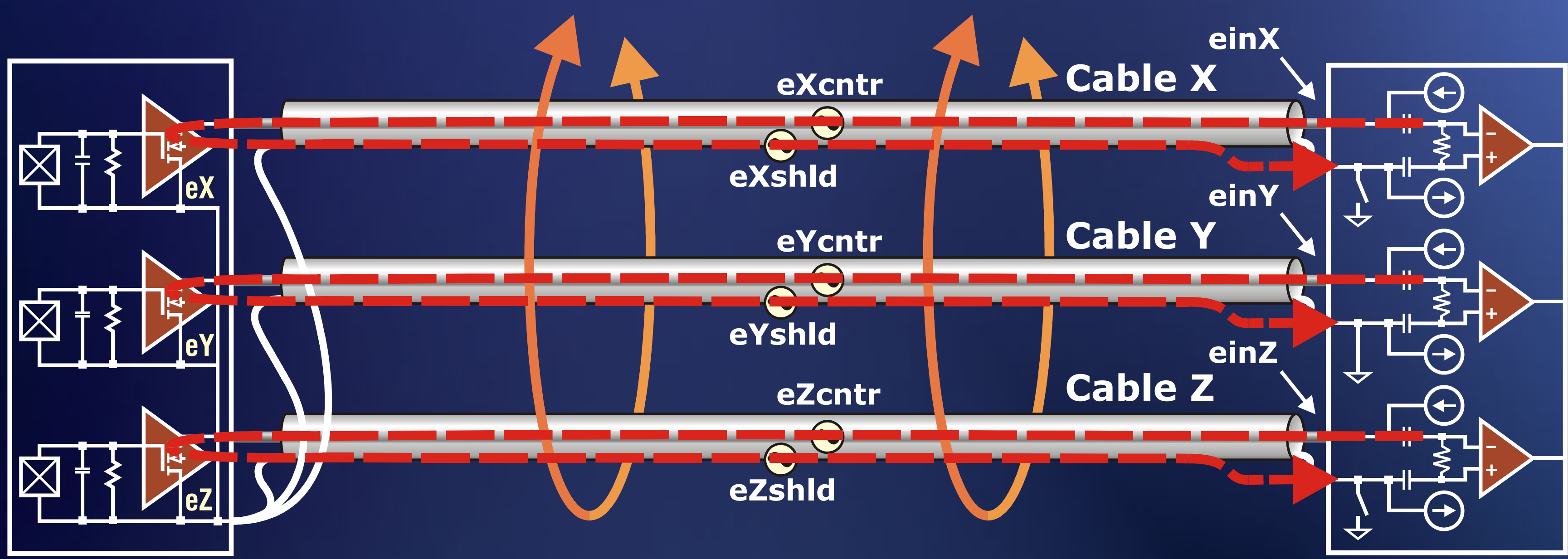
Optimal Signal Conditioner

- This signal, however, will appear as a common mode signal to channel X and Z inputs and will be eliminated by the CMRR of the differential amplifiers.



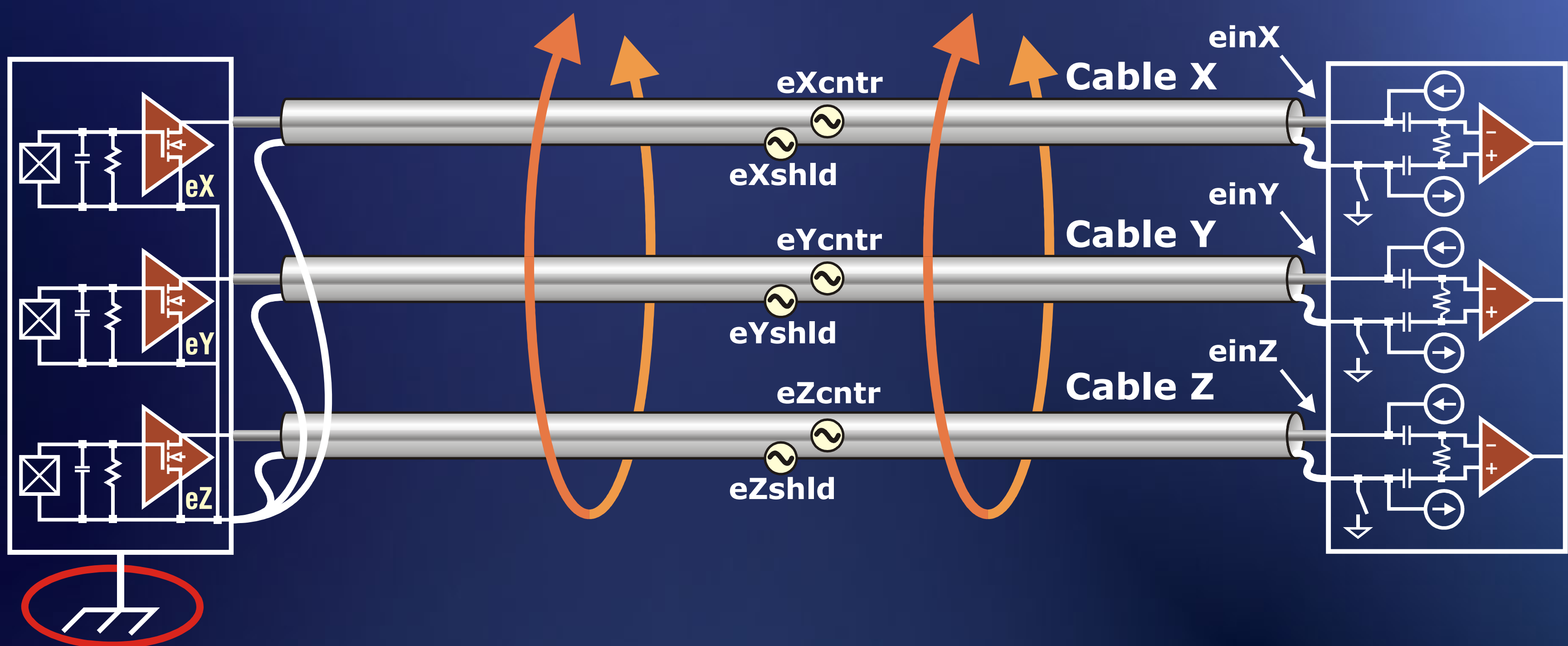
Optimal Signal Conditioner

- For this scheme to function properly the conditioner must have independently isolated input stages and must have high CMRR.



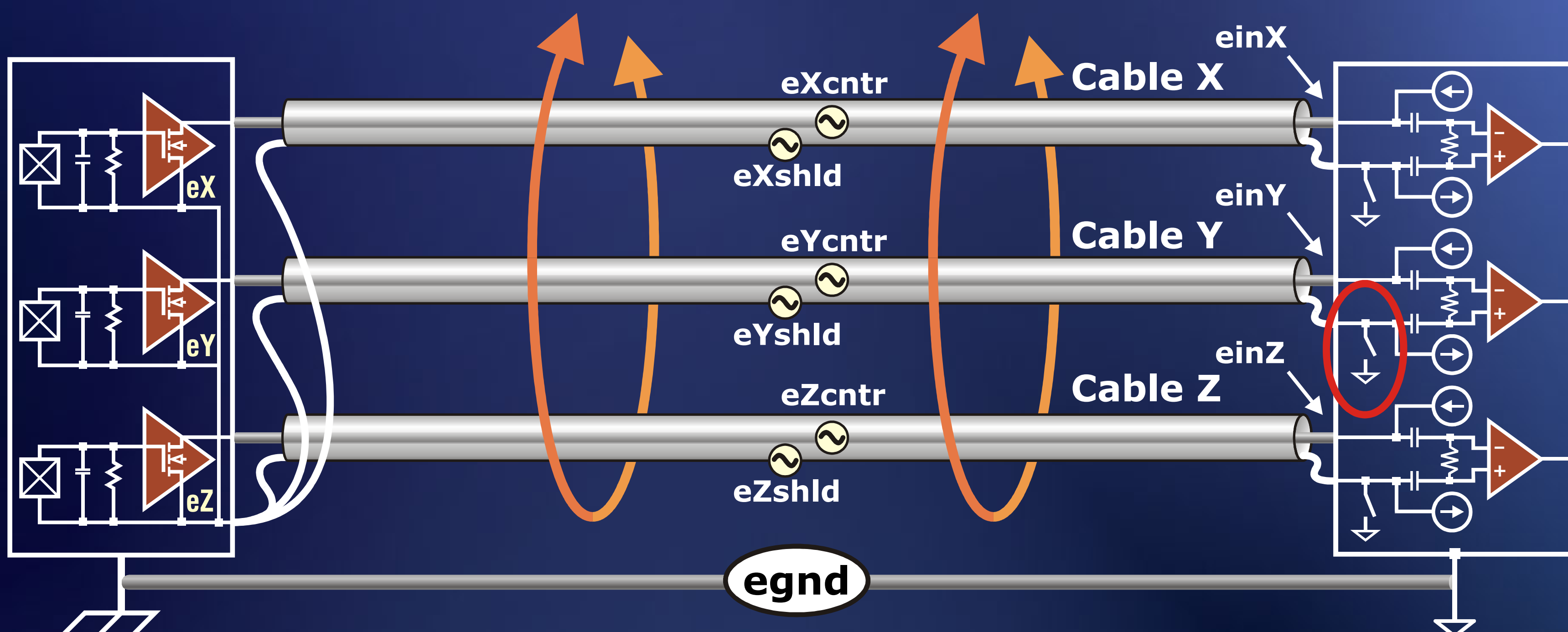
Optimal Signal Conditioner

- The isolation provides additional protection from ground loops in the event that the accelerometer case is grounded.



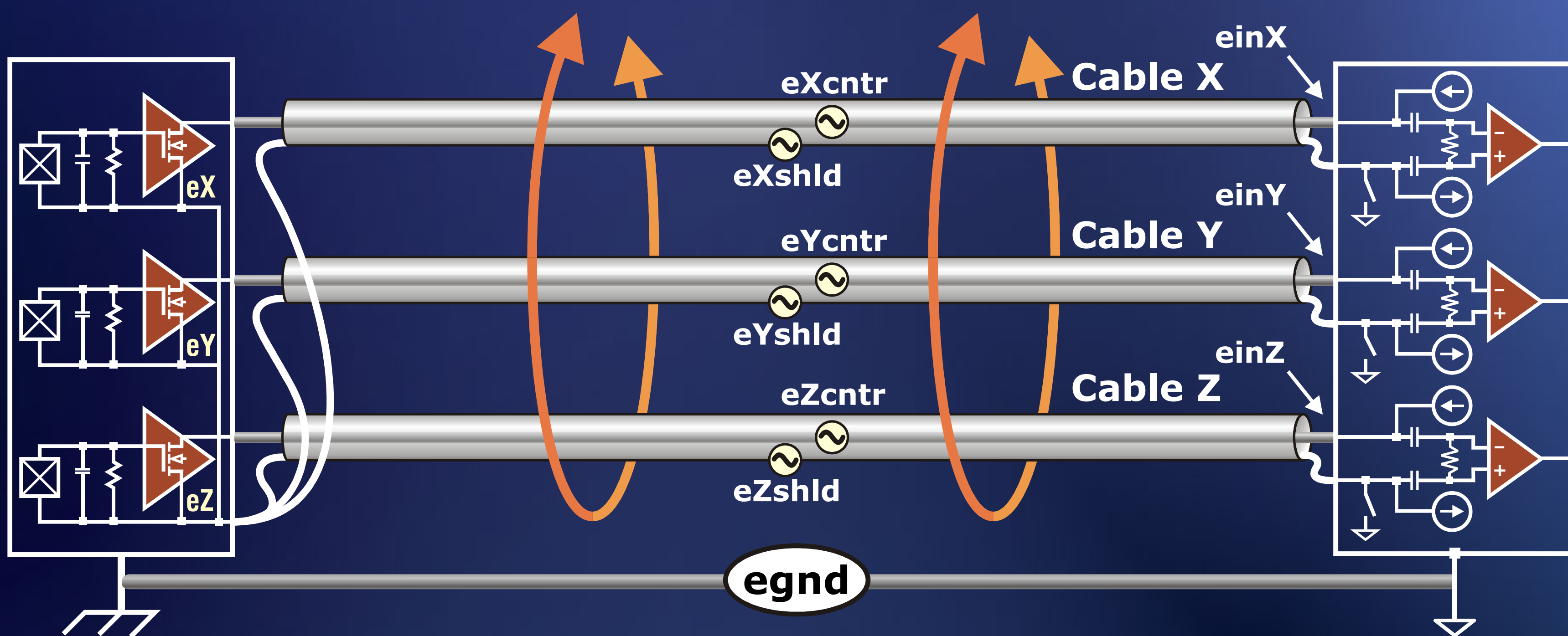
Optimal Signal Conditioner

- To eliminate the ground loop, all three channels would be isolated from ground and all three channels would be referenced to the distant sensor ground.



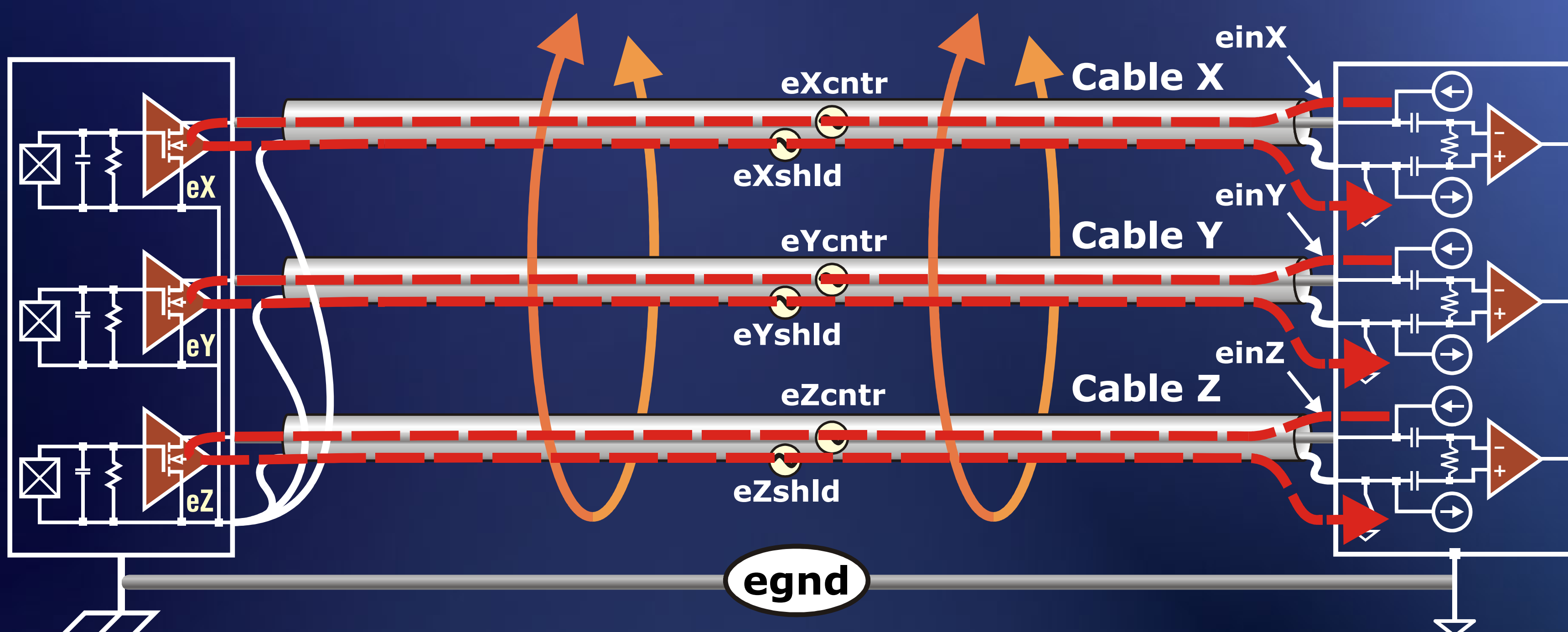
Optimal Signal Conditioner

- Any differential ground signal (egnd) will be eliminated by the CMRR of the differential input stages.



Optimal Signal Conditioner

- The isolated current sources guarantee that all IEPE current returns through it's own low connection and not through other return paths.



Experimental Result Test #3

Test Data:

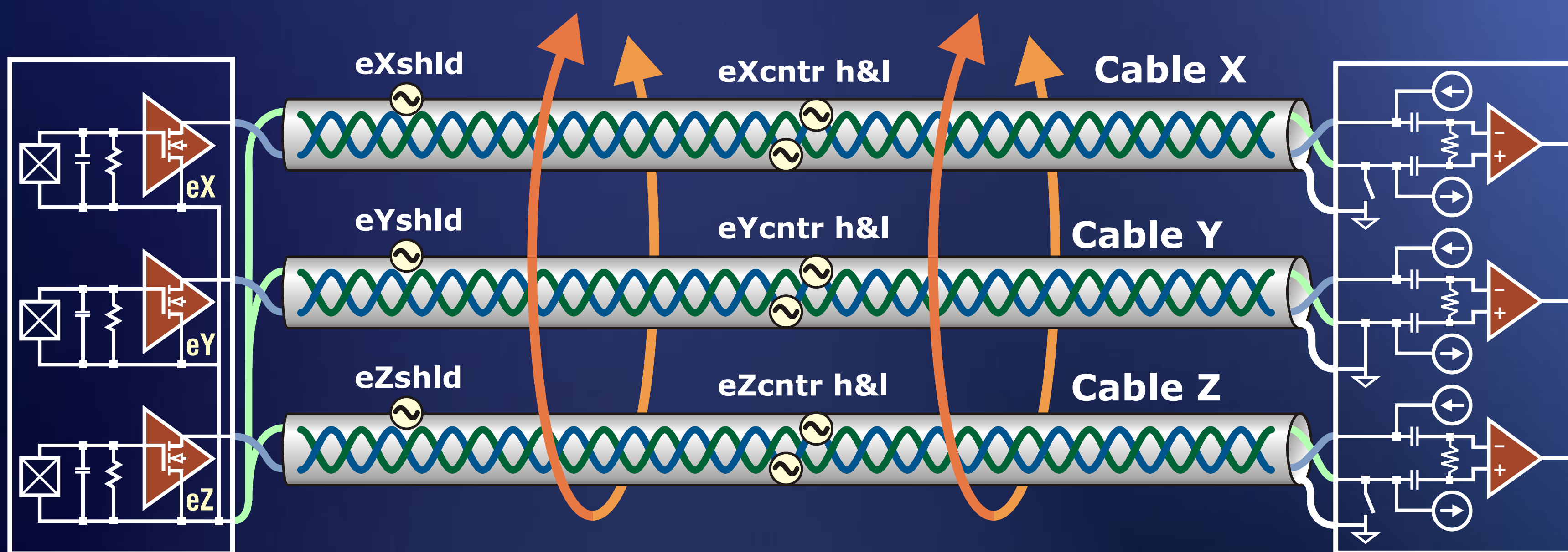
The proposed circuitry is breadboarded and tested using cables in the exact same location as in the original test setup.

	RMS reading	dB re Full Scale	Equivalent G's peak
Chan X	0.2 mVRMS	-91	0.0003
Chan Y	0.2 mVRMS	-91	0.0003
Chan Z	0.4 mVRMS	-85	0.0005

We see from this data that the proposed solution reduces the magnetically coupled noise signal in all three channels even with three separate coaxial cables arbitrarily placed within the magnetic field.

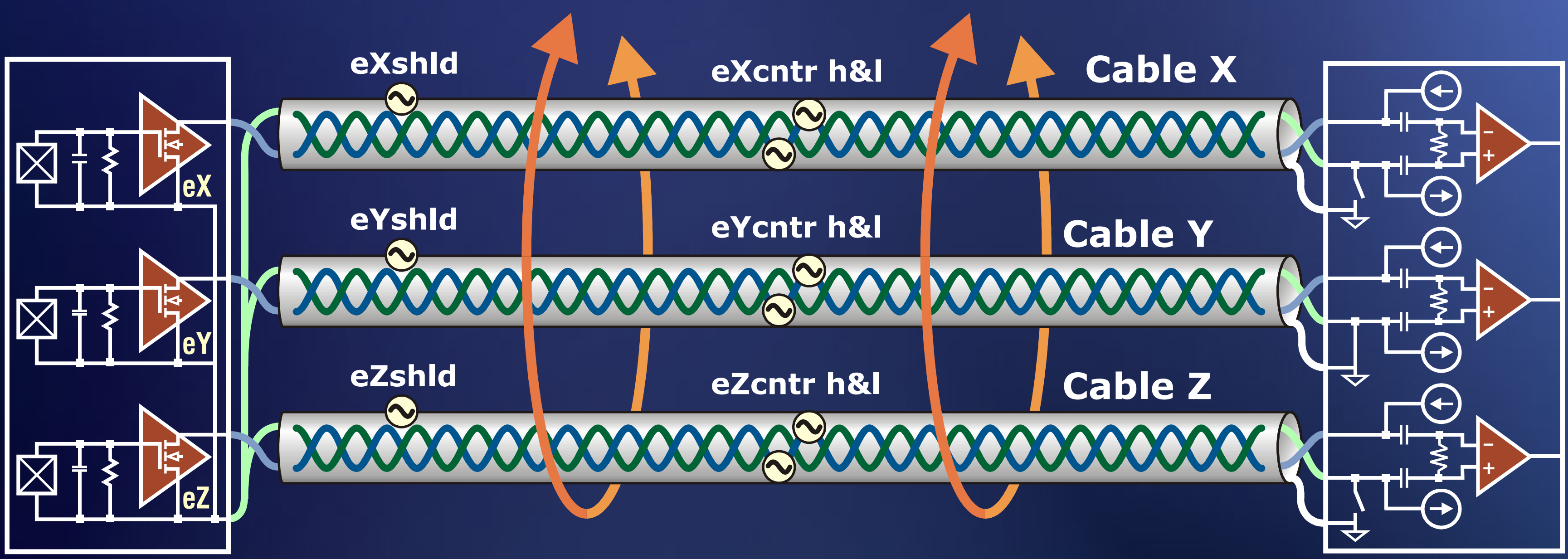
Optimal Signal Conditioner

- A final improvement that is useful for high magnetic field environments results from using shielded twisted pair cable in place of the coaxial cables.



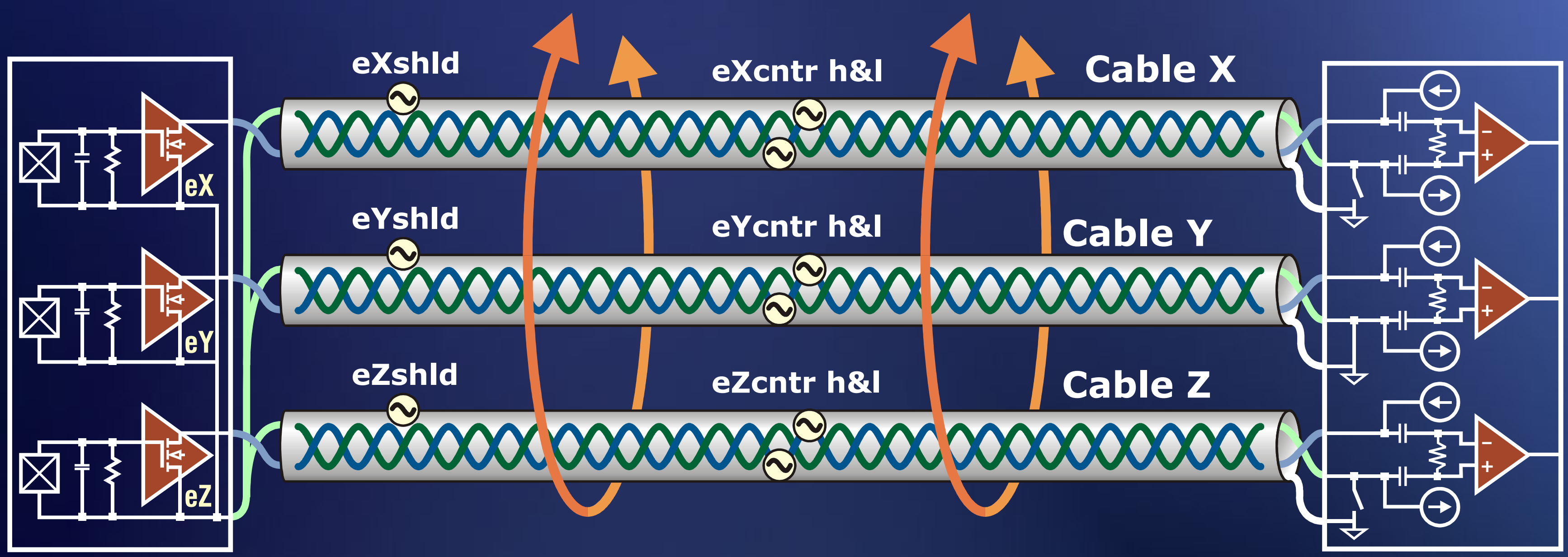
Optimal Signal Conditioner

- Due to the tight twisting of the high and low signal lines, these pairs will have almost identical induced signals.



Optimal Signal Conditioner

- Due to the improved match of the high and low signals, their error terms will more completely cancel in the loop equations written for each differential input amplifier.



Experimental Result Test #4

Test Data:

The three coaxial cables are replaced with a cable bundle containing 16 pairs of shielded twisted pair wires.

	RMS reading	dB re Full Scale	Equivalent G's peak
Chan X	0.16 mVRMS	-93	0.0002
Chan Y	0.10 mVRMS	-97	0.0001
Chan Z	0.07 mVRMS	-100	0.0001

Conclusions

- Segment analysis can be a useful analysis tool for understanding magnetically induced noise signals in cabled measurement systems.
- A voltage is induced in each wire in our cabling system exposed to a magnetic field. This is unavoidable! Our job is to assure the sum of induced voltages sums to zero in the amplifiers loop equation.

Conclusions

- The triaxial accelerometer presents a particularly difficult cabling problem. Even if the case is floating, we can still have induced shield currents due to the shared ground at the low connection.
- The shielded triplet cable is a good solution for short cable runs, but excessive X,Y,Z cross-talk may disallow this for longer cable runs or higher frequencies.

Conclusions

- For longer cable runs it was shown that there are NO suitable cabling schemes for connecting triaxial accelerometers to grounded single ended IEPE conditioner systems.
- A signal conditioner topology was proposed which solves these problems. This requires independently (per channel) isolated input stages with balanced (high CMRR) differential amplifiers.

Conclusions

- The signal conditioning technique described is employed in the Precision Filters Model 28316C. The 28316C is a 16-channel IEPE conditioner plug in card for the system 28000.
- 16 cards can be installed in the 16-slot chassis to provide 256 channels of independently isolated IEPE conditioning in 7U of rack space.

PRECISION FILTERS, INC.

Transducer Conditioner Systems ■ Filter/Amplifier Systems ■ Signal Switching Systems

Precision Filters, Inc.

240 Cheery Street

Ithaca, New York 14850

Phone: 607-277-3550

E-mail: sales@pfinc.com

Web: www.pfinc.com

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