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# **DIELECTRIC ANISOTROPY AND THE CASE FOR END-GRAIN: ORIENTATION OF THE CAPACITIVE LOAD PATH IN MAGNETICALLY NEUTRAL WOODEN CABLE SUPPORTS**

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# Dielectric Anisotropy and the Case for End-Grain: Orientation of the Capacitive Load Path in Magnetically Neutral Wooden Cable Supports

A. Bosque, Y. Tanaka, M. Ferro, H. Park

Equatorial Audio Research Division, Mitad del Mundo, Quito, Ecuador (0.0000deg N)

Journal of Equatorial Audio Science, 2026.

## Abstract

A wooden cable support is a dielectric body held in the near field of a signal conductor, and its contribution to the installation is therefore a capacitance, distributed and orientation-dependent, in parallel with the cable. In the flagship treatment of timber neutrality grading (Bosque, Ferro, Park and Tanaka, 2026), grain orientation was identified as a design variable and end-grain-vertical milling was adopted on a combined mechanical and dielectric argument stated in a single section. This companion paper develops that argument in full. Wood is dielectrically anisotropic: both the relative permittivity  $\epsilon_{rL}$  and the loss tangent  $\tan \delta_L$  are higher along the grain than across it, the along-grain axis exceeding the two transverse axes because the tubular tracheid and vessel cell geometry and the bound-water dipoles that dominate the polarisation are aligned with the fibre. We report guarded parallel-plate impedance-analyser measurements of  $\epsilon_{rL}$  and  $\tan \delta_L$  for equatorial teak along all three anatomical axes (longitudinal L, radial R, tangential T) at 8, 12, and 16 percent moisture content from 20 Hz to 10 MHz, confirming an anisotropy ratio  $\epsilon_{rL} / \epsilon_{rT}$  of 1.24 to 1.31 at audio frequencies and 12 percent moisture. From these constants we build a distributed-capacitance model of a cable resting in a machined cradle above a wooden column and compute the per-block capacitive contribution for end-grain-vertical versus face-grain milling: the two orientations differ by a measurable margin, with end-grain presenting the lower cable-referred capacitance because it places the low-permittivity transverse axes in the horizontal plane where the cable field is strongest and reserves the high-permittivity longitudinal axis for the vertical load path, where it is electrically harmless and mechanically ideal. A grain-angle sweep locates the coupling minimum at true end-grain. We close by noting that end-grain was originally specified for compressive stiffness, and that the dielectric argument, arrived at independently and afterward, agrees with the mechanical one to the degree of confirming it.

## 1. INTRODUCTION

A cable support does not carry the signal. It sits beside it. This is precisely why its electrical role is so easily dismissed: a block of wood under a cable is manifestly not in the circuit, and it is tempting to conclude that its composition, its grain, and its orientation are matters for the cabinetmaker rather than the engineer. The flagship neutrality-grading paper (Bosque, Ferro, Park and Tanaka, 2026) argued the magnetic half of the case -- that a support in continuous contact with a conductor is part of that conductor near-field environment, and that its residual paramagnetic content is a measurable input to the installation rather than a decorative one. It disposed of the dielectric half in a single section. This paper is that section, expanded to the length the physics deserves.

The electrical fact that the block sits beside the cable rather than within it does not remove it from the circuit; it fixes the manner of its coupling. A dielectric body in the field of a conductor stores energy capacitively, and a distributed capacitance in parallel with a transmission line is a load, small but real, whose magnitude depends on the permittivity of the body and on how that permittivity is oriented relative to the field. Wood is not an isotropic dielectric. Its permittivity depends on direction, and a wooden support therefore has not one dielectric contribution but three, selectable at the milling bench by the angle at which the billet is cut.

The claim of this paper is narrow and quantitative. It is that the end-grain-vertical orientation specified for the Equatorial Elevation Block -- growth rings on the top face, fibres running vertically down the load path -- is the orientation that minimises the block cable-referred capacitance, that the minimum is measurable rather than notional, and that it coincides with the orientation already chosen on mechanical grounds. We are not claiming the effect is large. We are claiming it has a sign, a magnitude, and a preferred direction, and that a maker who mills the block the other way for the sake of a prettier face grain has moved the number in the wrong direction without knowing the number exists.

## 2. THE DIELECTRIC ANISOTROPY OF WOOD

Wood is a cellular solid built from long, hollow, axially aligned cells -- tracheids in softwoods, fibres and vessels in hardwoods such as teak -- whose long axis defines the grain. This geometry is the origin of the mechanical anisotropy every woodworker knows, and it is equally the origin of a dielectric anisotropy that is less widely appreciated but just as real and long since documented (James, 1975; Torgovnikov, 1993).

Three mechanisms make the permittivity direction-dependent, and all three favour the longitudinal axis. First, the cell walls themselves form continuous polarisable pathways along the fibre and interrupted ones across it, so interfacial (Maxwell-Wagner) polarisation at the numerous wall-lumen boundaries accumulates preferentially along the grain. Second, the bound water held in the cell walls -- the dominant contributor to wood permittivity at all but the driest states -- sits in an environment whose hydroxyl sites and micro-fibrillar scaffolding are themselves aligned with the fibre, so the orientational polarisation of the bound-water dipoles is easier along the grain than across it. Third, the two transverse directions, radial R and tangential T, differ from each other only slightly, and both fall well below the longitudinal value L. The result, consistently across the literature, is the ordering  $\epsilon_{rL} > \epsilon_{rR} \sim \epsilon_{rT}$ , with the same ordering in the loss tangent, and an anisotropy ratio  $\epsilon_{rL} / \epsilon_{rT}$  that is typically 1.2 to 1.5 for temperate



and tropical hardwoods in the hygroscopic range.

Absolute values are modest and moisture-dominated. Oven-dry wood sits near  $\epsilon_r = 2$  to 3, rising steeply and monotonically as moisture content increases, because each increment of bound water adds dipoles to the polarisable inventory. This steepness is the reason moisture content, not species, is the largest lever on a support dielectric contribution, and it is treated in Section 5. For the anisotropy argument the essential point is structural rather than numerical: the direction of highest permittivity is the direction of the fibre, and that direction is set by the woodworker, not by the tree.

### 3. MEASUREMENT: PERMITTIVITY AND LOSS ALONG THREE AXES

We measured  $\epsilon_r$  and  $\tan \delta$  on machined teak coupons cut along each of the three anatomical axes, so that the field applied by the parallel-plate cell ran, in turn, longitudinally, radially, and tangentially through the sample. Coupons were 40 mm square by 3.0 mm thick, faced flat and parallel to  $\pm 10$  micrometres, cut from three 5N-graded equatorial billets selected under the flagship protocol so that magnetic contamination could not confound the dielectric reading. Each coupon set was conditioned to equilibrium at three moisture contents -- 8, 12, and 16 percent -- in humidity chambers, and its moisture verified gravimetrically against oven-dry mass at the end of the run.

The cell was a guarded parallel-plate fixture of the type described previously (Tanaka and Park, 2022), driven by a Keysight E4990A impedance analyser from 20 Hz to 10 MHz. The guard ring suppresses fringing so that the measured capacitance corresponds to a defined electrode area and the extracted permittivity is the material bulk value rather than an edge-contaminated estimate; loss tangent is read directly as the dissipation factor of the fixture. Contact was made through thin conductive-elastomer interlayers to accommodate the residual surface roughness of the milled faces without an adhesive that would contribute its own polarisation.

At 12 percent moisture content and 1 kHz, teak returned  $\epsilon_L = 2.64$ ,  $\epsilon_R = 2.09$ , and  $\epsilon_T = 2.02$ , an anisotropy ratio  $\epsilon_L / \epsilon_T$  of 1.31 and  $\epsilon_L / \epsilon_R$  of 1.26; the two transverse axes agreed to within 4 percent, as expected. The loss tangent tracked the same ordering:  $\tan \delta$  was 0.021 along the grain and 0.014 to 0.015 across it. Across the audio band from 20 Hz to 20 kHz the permittivities were flat to within 3 percent and the anisotropy ratio held between 1.24 and 1.31. Raising the moisture content to 16 percent lifted every value --  $\epsilon_L$  reached 3.08 -- and, notably, widened the anisotropy slightly, because the added bound water polarises preferentially along the favoured axis. Drying to 8 percent compressed both the absolute values and the ratio. The anisotropy is thus not a fixed material constant but a moisture-modulated one, strongest where it matters least (wet) and weakest where the material is driest; at the 12  $\pm 1$  percent delivery specification it is comfortably resolved and stable.

### 4. THE DISTRIBUTED-CAPACITANCE MODEL OF CRADLE, CABLE, AND COLUMN

To convert three permittivities into a design decision we need the geometry of the coupling. The cable does not sit on a flat block; it rests in a cradle, a shallow radiused groove machined into the top face, so that a finite arc of the cable jacket is separated from the wood by only the jacket wall thickness. The wood directly beneath that arc -- a short vertical column running from the cradle floor down into the body of the block -- is where the field between the conductor and any distant ground return is strongest and where the great majority of the cable-to-support capacitance is stored. Wood further out, and further down, contributes with a rapidly falling weight as the field spreads and weakens.

We model this as a distributed capacitance per unit length of run, integrating the local field energy through the wood volume beneath and around the cradle with the permittivity tensor of the wood inserted axis by axis. The construction is standard for an anisotropic dielectric: the vertical field component samples the vertical-axis permittivity, the horizontal components sample the horizontal-axis permittivities, and because the cradle concentrates the field into the near-vertical region just under the conductor while the return paths that close the capacitance run outward and downward through the flanks of the column, the horizontal permittivities carry the larger share of the stored energy. The model output is a single figure of engineering interest: the capacitance the block adds to the cable, in picofarads per block, as a function of how the permittivity tensor is oriented.

Two orientations are of practical interest. End-grain-vertical milling puts the longitudinal axis L vertical, down the load path, and leaves the two low transverse axes R and T lying in the horizontal plane. Face-grain (flat-sawn, fibres horizontal) milling lays the longitudinal axis L into the horizontal plane, where it is sampled by the strong horizontal field components, and stands one transverse axis vertically. Feeding the measured 12 percent constants into the model for a representative cradle geometry (12 mm cable diameter, 3 mm radiused cradle, 60 mm block height, a nominal ground return at chassis distance) yields approximately 1.9 pF per block for the end-grain orientation and approximately 2.3 pF per block for the face-grain orientation -- a difference near 0.4 pF, roughly 18 percent, arising from nothing but the angle of the cut. Per block this is small. It is also real, repeatable, one-signed, and free: it costs the maker only the decision to orient the billet correctly, and it accumulates across the several blocks of a full run.

### 5. GRAIN-ANGLE SWEEP AND MOISTURE SENSITIVITY

The two named orientations are the endpoints of a continuum, and it is worth confirming that end-grain is a true minimum rather than merely the better of two arbitrary choices. We machined a series of coupons at grain angles from 0 deg (fibre vertical, true end-grain) through 30, 45, 60, to 90 deg (fibre horizontal, face-grain) relative to the load axis, and measured each in the cradle



model geometry with a conductor energised above it. The cable-referred capacitance rose monotonically with grain angle, from the end-grain minimum at 0 deg to the face-grain maximum at 90 deg, following closely the cos-squared weighting the tensor model predicts as the high-permittivity longitudinal axis rotates progressively into the horizontal field. The curve is shallow near 0 deg -- a few degrees of milling error costs almost nothing -- and steepest through the middle of the sweep, so the penalty for a genuinely careless cut is larger than the penalty for an imperfect but well-intentioned one. The minimum is at true end-grain, and it is a minimum, not an inflection.

Moisture content shifts the whole curve vertically without moving the location of the minimum. Because permittivity rises steeply with bound water, a block that has drifted from 12 to 16 percent moisture adds more capacitance in absolute terms than the entire end-grain-to-face-grain difference at fixed moisture -- the moisture lever is larger than the orientation lever. But the two are independent: wetting the wood raises the floor, it does not change which orientation is lowest. Orientation and conditioning are therefore complementary controls, and both must be exercised. This is the measured basis for kiln-drying every graded billet at origin to 12 +/- 1 percent and for the annual moisture check in the maintenance schedule: the orientation is milled in permanently and cannot drift, but the moisture that scales it can, and a support left to equilibrate with a humid room slowly surrenders the margin the milling bench secured.

We note in passing that the transverse-axis agreement measured in Section 3 means the choice between radial and tangential presentation in the horizontal plane is immaterial to within measurement uncertainty; the block may be indexed rotationally about its vertical axis for the best appearance of the top-face rings without dielectric consequence, provided the fibres remain vertical.

## 6. DISCUSSION: TWO ARGUMENTS, ONE ORIENTATION

The end-grain orientation was not adopted for its dielectric behaviour. It was adopted because end-grain is the stiffest and strongest way to load wood in compression: with the fibres standing vertically, a downward load is carried along the tubular cells in their strongest direction, and the block resists the static weight of a cable run and the settling of an installation with the least creep and the least dimensional change. That is an old and uncontroversial piece of timber engineering, and it fixed the milling specification before any permittivity was measured.

The dielectric measurements reported here were made afterward, and they could in principle have disagreed with the mechanical choice -- the along-grain axis might have been the low-permittivity axis, in which case standing it vertically would have been mechanically right and electrically wrong, and a compromise would have been forced. They did not disagree. The along-grain axis is the high-permittivity axis, so standing it vertically removes it from the horizontal plane where the cable field is strongest, which is exactly what the capacitance model asks for. The orientation that is mechanically ideal is, independently, the orientation that is dielectrically quietest. The two arguments were constructed from different physics, at different times, by people solving different problems, and they select the same cut.

We attach no mystical weight to this agreement; anisotropic materials frequently have their stiff axis and their high-permittivity axis aligned, because both properties trace back to the same aligned microstructure, and teak is such a material. But the practical consequence stands. A maker following the mechanical argument alone arrives at end-grain and, without intending to, minimises the capacitive coupling as well. A maker who overrides the mechanical argument for the sake of a decorative face grain loses on both counts at once. The convergence is not a coincidence to be marvelled at so much as a reason to trust the specification: when two independent lines of reasoning terminate on the same number, the number is more likely to be right.

## 7. CONCLUSION

Wood is a dielectrically anisotropic body, and a wooden cable support is that body held in the near field of a conductor. Its contribution to the installation is a small distributed capacitance whose magnitude the maker sets, unknowingly or otherwise, at the milling bench. We measured the three-axis permittivity and loss of equatorial teak, confirmed the expected ordering  $\epsilon_{\text{L}} > \epsilon_{\text{R}} \sim \epsilon_{\text{T}}$  with an anisotropy ratio near 1.3 at the delivery moisture content, and carried those constants through a cradle-and-column capacitance model to a figure of merit -- picofarads per block -- that differs measurably between end-grain and face-grain milling. End-grain is the lower of the two, by roughly 0.4 pF and 18 percent in a representative geometry, and a grain-angle sweep confirms it as a true minimum.

The margin is small per block and we decline to overstate it. What we assert is only that it is real, that it has a preferred direction, and that the preferred direction is the one already specified on mechanical grounds. The Equatorial Elevation Block is milled end-grain-vertical because end-grain is the stiffest way to carry a compressive load; the dielectric analysis reported here was undertaken afterward and confirms that the same cut is also the dielectrically quietest. Every block ships end-grain up, kiln-dried to 12 +/- 1 percent, unfinished, with its grade and its measured constants on the certificate. We invite the reader to ask any other maker of wooden supports which way their grain runs, and why.

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