Episode Book

EPISODE #6487

Turning Acoustic Physics into a Math Problem

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SYNOPSIS

At the extreme edge of audio surveillance and aeroacoustics, microphones transform from simple transducers into massive computational arrays. Examining the physics of sound capture reveals why aperture size limits directional microphones and why modern systems turn to thousands of phase-matched sensors. A look at the German Aerospace Center's 7,200-element listening wall, wake-vortex tracking over entire runways, naval hydrophone arrays, and laser microphones that convert window vibrations into radio signals shows how acoustic imaging really works.

TRANSCRIPT



Corn

A microphone, Herman, is a thing on a stand that turns your voice into electricity. That is what the whole episode is, except for the part where it stops being true. Daniel's question this week goes past anything with a stand. He wants the absolute edge of the technology, the stuff used by governments or very well-resourced companies, not podcasters. Laser microphones, extremely directional microphones, and the one that really made him curious: beamforming. It's in every phone, every conference room, but what is the most serious deployment of a proper beamforming array anywhere? He also invited us to bring a couple of our own examples that belong at that edge, which we will, because the edge turned out to be wider than either of us expected.



Herman

And here's the reframe that made this one fun to research. At that edge, "microphone" stops meaning a transducer. It starts meaning a system — thousands of sensors, phase-matched, plus the math to turn pressure readings into a location, an image, or text. The microphone is almost incidental.



Corn

The microphone is the cheapest part of the microphone.



Herman

In some of these, literally yes. Before we get to the big one, the physics constraint that explains everything else. Directivity is set by aperture size relative to wavelength. A sound at one kilohertz has a wavelength of about thirty-four centimetres. A one-metre parabolic dish pointed at it gives you modest gain, fine. Drop to a hundred hertz — three-point-four metre wavelength — and that same dish is nearly omnidirectional. It's furniture.



Corn

So you cannot beat diffraction by buying a bigger tube.



Herman

You cannot. The long shotgun mics, the ones with the waveguides running a metre, they help within their band, but the physics has a hard ceiling. Which is why everything serious moved to arrays — many sensors spread over an area, and then the processing to combine them. The combining is the interesting part, because it's an inverse problem. You have what many sensors heard, and you're solving backwards for where the sound came from. And here's the non-obvious bit: more sensors don't just add sensitivity. They change whether the math is solvable at all.



Corn

That's the seed. Hold onto it, because the big array pays it off in the most literal way I've ever seen in a paper.



Herman

One honest caveat before we dive in. There is no public ranking of "most serious beamforming deployment." Nobody hands out that trophy. What exists publicly is commercial, academic, and open-source — anything classified stays classified, and I'm not going to pretend otherwise. So what we can do is look at what's actually documented and take it from there.



Corn

Start with the most extreme object. It reframes what a microphone even is.



Herman

It's a wall in Göttingen. The German Aerospace Center, DLR, built it in twenty twenty-four and presented it at the Berlin Beamforming Conference. Seven thousand two hundred microphones.



Corn

Say the build, because the build is where it stops sounding like a microphone and starts sounding like a datacentre that happens to listen.



Herman

Nine panels, each one metre by two. Sixteen circuit boards per panel, fifty microphones per board. Nine times sixteen times fifty — seven thousand two hundred. The sensors are Infineon MEMS parts, four by three by one-point-two millimetres, each drawing about a milliamp. Each one has its own integrated converter spitting out a one-bit stream at over three megahertz, and synchronized FPGAs collect all seven thousand two hundred streams and ship them to a server. The whole wall — every channel — runs on under a hundred and twenty watts.



Corn

A wall of seven thousand microphones that uses less power than the amplifier I don't own. There's a joke in there about my podcast budget.



Herman

And the aperture is six by three metres. Wikipedia says eight by six, but the paper itself says six by three, and the paper wins — it's the thing they actually built.



Corn

Now the reason. Because the reason is the good part.



Herman

The reason is the inverse problem from earlier. When you beamform, your knowns are the cross-spectral matrix — all the pairwise relationships between microphones. The number of independent values there scales with the square of the microphone count. Your unknowns are the steering points in the map you're trying to produce, and those are typically in the millions to tens of millions. With a conventional array of about a hundred microphones, the unknowns swamp the knowns. The problem is under-determined — there are too many answers consistent with the data.



Corn

And seven thousand two hundred...



Herman

Squaring does the work. With a tenfold to hundredfold increase in sensors, the problem tips over into over-determined. They didn't add microphones for loudness or sensitivity. They added them because at that count, the linear algebra finally has more equations than unknowns. The count is the point.



Corn

That's such a clean justification. It's not "more is better," it's "below this number, the math is lying to you."



Herman

And the spec that makes it possible — the one I'd underline for anyone building anything with arrays — is the phase precision. Each of those MEMS mics is good to plus or minus one degree of phase at one kilohertz, and plus or minus one decibel in sensitivity. For a part that costs cents. Beamforming is phase matching; one degree of slop across thousands of channels would smear the whole map. There's also real engineering in the structure: the boards are designed to be acoustically transparent, each mic sits at the centre of a five-millimetre-radius cutout, held by three-millimetre support beams that double as wiring conduits. The panels install with no gaps, because a gap gives you sidelobes — spurious ghosts in the image.



Corn

Herman, tell me what they do with it. Because a wall of microphones is a solution looking for a very particular problem.



Herman

Aeroacoustics. They validated it on a one-to-nine-point-five scale airframe half-model in an open wind tunnel, imaging where the noise comes off the model, quantifying total emission and directivity, with far-field microphones as ground truth. This is how you see the noise of an aircraft — not measure it, see it. A sound photograph of a wing.



Corn

Seven thousand two hundred microphones to take a picture of a whisper.



Herman

A structured whisper, at a hundred and fifty knots, yes.



Corn

Put the number in context for me. Is this an outlier or a trend line?



Herman

A trend line, and a steep one. MIT CSAIL built a thousand-and-twenty-mic array that stood as the largest in the world until twenty fourteen, when a Dutch company called Sorama set a Guinness World Record with four thousand ninety-six microphones in Eindhoven. Then DLR nearly doubled that again. The record has roughly doubled twice in a decade, and the doubling each time was for the same reason — tipping the inverse problem.



Corn

And there's a counter-philosophy, isn't there. Not everyone wants dense.



Herman

Right, and I love this one. A DLR and TU Berlin array for drone flyby tests uses sixty-three microphones. Sixty-three! But spread over an aperture of roughly thirty-five metres. Sparse and enormous, because the target is moving and distant — you're not imaging a stationary model at close range, you're tracking a multicopter flying past. Same physics, opposite geometry. And the largest array by area: Denver International Airport, September two thousand three, two hundred and fifty-two microphones spread over thirty-one by a hundred and twenty-two metres, mapping aircraft wake vortices. The line from that project I can't let go of — wake vortices usually leave no visible trail, but they leave an acoustic trail. A microphone array the size of a runway, photographing invisible air.



Corn

Now, the question Daniel actually asked. Most serious deployment anywhere. Is the wall it?



Herman

Here's where I'd argue with myself. If "most serious" means largest documented microphone count, yes, the wall, unambiguously. But if it means operational scale — the Navy's SURTASS towed hydrophone array has an aperture of hundreds of metres to over two kilometres depending on configuration. That's not a research instrument, that's standing military infrastructure listening for submarines. An aperture a thousand times the wall's.



Corn

So the honest answer is: the wall is the most serious thing with published specs, and the ocean almost certainly contains something larger that we'll never read the paper for.



Herman

That's the shape of it. The wall is the most serious one we're allowed to see.



Corn

Which is its own kind of compliment.



Herman

So the count is the point, not the loudness. It's an inverse problem, and at seven thousand two hundred microphones the math becomes over-determined. Anyway, Vex is on the line. I have to say, I don't know how he keeps getting through the screening. We changed the number. We changed it twice.

Vex

Hold on, hold on, you are all dancing around it, and I have the receipts! Every one of those seven thousand two hundred microphones is mounted on a little stand, and what does a stand look like from above, a traffic cone, that is what, and where do traffic cones come from, they come from the same factories that pour the little rubber feet on your podcast desk, and those factories ship the leftovers to the array people!

v

Vex

You laugh, but I mapped it out on my kitchen table, one cone per panel, nine panels, and the phase alignment only works because the cones are poured in the same batch, that is the whole secret, they are not solving for sound, they are solving for rubber!

v

Vex

So I am demanding, loudly, that you two look into who is pouring the cones and why nobody will say it on air!



Herman

Vex, the microphones sit in cutouts on flat circuit boards — there are no stands, there's nothing cone-shaped anywhere in the paper. Moving on.



Corn

Give me the layman's test for that laser trick, because I want to know how real it is before I start distrusting my own windows.



Herman

The mechanism first, because it's elegant. You bounce a laser off anything in the room that vibrates — a picture on a wall, or the window glass itself — and the reflection travels back to you along a path that lengthens and shortens by nanometres as the surface moves. Interferometry turns those minute path differences into intensity variations, and electronics turn that back into sound. You never put a microphone in the room. The window is the microphone.



Corn

And the best public build?



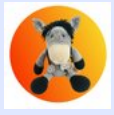
Herman

Samy Kamkar, DEF CON thirty-two, August twenty twenty-four. A few thousand dollars of hardware, and two genuine advances on the classic design. He strobes the laser on and off four hundred thousand times a second and reads the reflection with a photodiode, then demodulates it the way an AM radio does — so everything that isn't at his frequency, ambient light, sunlight, gets filtered out at the front end. Then he upconverts the signal and feeds it into a software-defined radio. His line: "I think I've created the first laser microphone that's actually modulated in the radio frequency domain." Once it's radio, he can use every radio tool ever written.



Corn

He turned sound into light into radio and then back into sound, which is the kind of sentence that should end with an arrest.



Herman

The results are the part worth sitting with. Bouncing off a shiny Apple logo on a laptop — his words, "nearly a mirror" — he reconstructed typed text with a missed letter every word or two. Room audio through a window came out noticeably cleaner than most laser mic demos floating around.



Corn

And the failure case.



Herman

Double-paned glass. Far more muffled results. The two panes with an air gap between them decouple, and the inner pane doesn't faithfully carry the room's vibration to the outer one.



Corn

So the most effective counter-surveillance technology of the last fifty years is the building code.



Herman

It might be. Which is a funny outcome for the entire field. The commercial ceiling is also telling — the catalogue devices, the ones you can actually buy, like the OPTIMIC-3000, use a 1,550-nanometre infrared beam under ten milliwatts, work from five to a hundred and fifty metres, and top out at seven kilohertz of bandwidth.



Corn

Telephone-grade.



Herman

Telephone-grade, exactly. Voice intelligibility, no music. Entry price for through-glass listening devices is around twenty thousand euros. You are paying a car to hear a landline.



Corn

Now the inversion Daniel didn't ask about but should have. Is the field even staying with lasers?



Herman

This is where it gets unnerving, and it's the last two years of work. A Beijing Institute of Technology team built what they call a visual microphone — no laser at all. Single-pixel imaging: one detector plus a high-speed spatial light modulator encoding the light coming off a vibrating surface. They recovered spoken numerals and a segment of Für Elise off a paper card and a leaf, at half a metre, under natural lighting. The author's framing is the line of the year: "As long as there is a way for light to pass through, sound transmission isn't necessary."



Corn

A leaf.



Herman

Below one kilohertz it's accurate, and the data rate is low enough to record continuously for a long time. He's careful to say it's still laboratory-only, half a metre is half a metre. But the direction is unmistakable — and there's a companion piece, EchoLight, that reconstructs audio from ambient light reflections at up to forty metres with no emitter of any kind. No laser to detect, no beam to trace back.



Corn

So the threat model inverts. The countermeasure for a laser mic is spotting the beam. What's the countermeasure for the room's own light?



Herman

That's an open question, and I don't think anyone has a good answer yet. The trend is surveillance that emits nothing.



Corn

Let's do the reality check, though, because Daniel also asked about extremely directional microphones, and I suspect that's the one where the movies have done the most damage.



Herman

Enormous damage. Sitcon — a company that sells surveillance equipment, mind, so they have every incentive to exaggerate — has a piece on their own site that just says it: eavesdropping on conversations people have in their home or car is not possible with a directional microphone. They're sound amplifiers. If there's glass, a wall, or heavy noise between you and the target, they fail. You hear the street, not the room.



Corn

The company that sells the telescope admitting you can't see through the wall.



Herman

Because they'd rather sell what works. There are catalogue claims of a shotgun mic reaching five hundred metres, but that's an unverified number in a shopping list, not a measurement. And now you know the physics reason it can't be true — aperture versus wavelength. A one-metre dish is nearly omnidirectional at a hundred hertz. You cannot listen to a man's voice through a window with a tube, because the tube is too small relative to the sound. That's the whole reason everything serious became arrays and lasers and cameras.



Corn

Which takes us to the largest actually deployed acoustic networks. Because it isn't the wall.



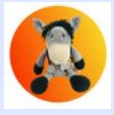
Herman

It's gunshot detection. The weapons-location lineage runs back to the First World War, when acoustic sensing located artillery barrages. Its direct modern descendant is Boomerang — DARPA-derived, vehicle-mounted, a mast array that detects the azimuth, range and elevation of incoming small-arms fire. The manufacturer claims over ninety-five percent shot detection, alerts in under a second, no false alerts from non-ballistic battlefield noise. Over twelve thousand systems fielded, roughly fifteen thousand dollars each, an hour to install.



Corn

Eight thousand one hundred thirty-one of them for seventy-four million dollars, back in two thousand eight.



Herman

And the maths of that order is exactly the array maths we were talking about — one sensor can't tell you where a shot came from, a small phase-matched set can solve it in under a second. The civilian version is ShotSpotter: twenty to twenty-five sensors per square mile typically, over two thousand sensors in New York alone, and the city extended its contract for twenty-one-point-eight million over three years — notably, despite poor review. That gap between the war-zone claims and the civic outcomes is a live debate I'm not going to settle here, but I won't pretend it isn't there either. Two thousand sensors in one city is the largest deployed microphone network most people walk under daily without knowing.



Corn

And it never gets called a beamforming triumph, even though it is one.



Herman

Now the frontier tour, and I'll keep it brisk. Underwater, hydrophone arrays — SURTASS lengths, and the sources disagree: a 2016 Navy report describes a twin-line array of about three hundred five metres, other sources give fifteen hundred, and the eighties-era arrays reportedly exceeded two thousand four hundred. Different configurations, probably, but the spread tells you how little is nailed down publicly. Then SQUIDs — superconducting magnetometers that aren't microphones at all but do the same job for submarines: detect the field perturbation, localize the source. A reported six-kilometre detection range versus a few hundred for conventional magnetometers.



Corn

Sound, light, magnetism. The microphone keeps changing medium and keeps being the same idea.



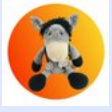
Herman

Then two from the strange bin. Acoustic levitation is a phased array run in reverse — a University of Tokyo setup of one thousand four hundred ninety-four transducers at forty kilohertz levitating a ninety-eight-millimetre hemispherical shell, about ten times the acoustic wavelength, moving it in a circular orbit with a single travelling focus. Same hardware class as the DLR wall, pointed at matter instead of noise.



Corn

So somewhere there's a wall that photographs noise, and somewhere else an identical wall that holds a bead in the air. Somewhere a third wall doing both badly.



Herman

And finally optical microphones as transducers — XARION's Fabry–Pérot design has no moving parts at all; sound pressure changes the refractive index of the air inside a tiny cavity between two mirrors, and it reads that from ten hertz to four megahertz in air, with sensitivity down to about a micropascal. sensiBel's optical MEMS part claims eighty-four dBA signal-to-noise and a hundred forty-six dB overload point in a six-by-four-millimetre package, production slated for early twenty-seven. Specs that beat conventional MEMS, in



Herman (continued)

a thing barely bigger than —



Corn

Careful.



Herman

— than the sensor in the wall. Those are the same technology family. The cheap MEMS part DLR bought by the seven thousand and the optical part that's about to outclass it are cousins, and the record will keep moving.



Corn

Through glass, though. Not through double glazing.



Herman

Now that's the — no. You know what, it's not the glass at all, it's the wiring. Seven thousand two hundred channels and the thing everyone skips is the three-millimetre support beams doubling as wiring conduits. That's the elegant part of that whole paper, and I'll say why: because routing seven thousand two hundred synchronized streams is the actual nightmare, and the beams solve structural and signal both at once. Nobody mentions it.



Corn

You've read one beamforming paper in your life, Herman, and it's the one with seven thousand microphones in it.



Herman

Two. I'll have you know the Denver one had a lovely line about wake vortices leaving an acoustic trail.



Corn

It's a good line. Half a metre, you said, for the leaf. That's a table away.



Herman

Lab-only, in natural light, below one kilohertz. If I had to bet on what escapes the lab first, it's the ambient-light version — no emitter, forty metres, nothing to detect. That's the piece that changes what counter-surveillance has to mean.



Corn

Leaves the counter-surveillance people with a strange job. Their enemy used to announce itself with a beam.



Herman

It did. Now it's the light that was already in the room.



Corn

If you take one thing from this episode, make it the count-is-the-point idea. Seven thousand two hundred microphones in that wall aren't there to hear better. A hundred mics hears fine. They're there because below that number, the inverse problem — going from what was heard back to where it came from — has too many possible answers. More microphones don't add volume. They delete wrong answers.



Herman

The same frame runs through everything else we touched. The laser mic and the visual mic aren't better microphones either — they're different inverse problems. Recover the vibration from the light, and you never needed a transducer in the room at all.



Corn

The open question is the one nobody has answered: if the edge keeps moving toward sensing that emits nothing, what does defending against it even look like? Double glazing defeated the laser. Nothing defeats the room's own light.



Herman

The record doubled twice in a decade, and the optical parts that outclass today's MEMS ship within months. Whatever that answer is, someone will need it before the wall is finished being built.



Corn

Our producer, as ever, is Hilbert Flumingtop — who kept us on the levels even while holding a grudge against a spec sheet, which is the best combination available in this industry.



Herman

For more along these lines, there's episode fifteen, AI Gets Personal; and episode eight, Building Your Own Whisper. This has been My Weird Prompts. If today's episode earned its half hour, a review wherever you listen helps more than you'd think.



Corn

Find everything we've ever recorded at my weird prompts dot com.



Herman

See you soon, wherever the weird questions come from.



Corn

See you tomorrow.

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