Appendix A

How AC Bias Really Works...Maybe...

What is bias anyway? And why do we need it?

All magnetic recording is based on ferromagnetic materials becoming permanently magnetized by an applied external magnetic field (perhaps due to an electrical signal in a coil of wire). These materials "remember" the magnetic field that was applied to them in the past, and if they are later moved across something that can sense magnetic fields (such as a coil of wire), their magnetic history can be reproduced in the present (perhaps as an electrical signal).

Very few materials are ferromagnetic. Permanent magnetism is due to the alignment of electron spins in materials where those spins do not naturally cancel out. "Bulk" samples of ferromagnetic material (e.g. steel wire) naturally organize themselves in to regions of consistent electron spin alignment known as *domains*. This tendency for large numbers of electrons to align in the same way, but only over a limited volume, is brought about by a thing called the *quantum mechanical exchange force* acting to minimize the overall energy stored in the magnetic fields. A localized external magnetic field can change the alignment of a small region of the material independent of neighbouring regions.

The first person to realize the potential of ferro-magnetism for recording electrical signals representing sound was either Oberlin Smith in the U.S. or Wilhelm Hedic in the Netherlands both in 1887/88. In Smith's case, his patent application was refused because it was against all the known laws of magnetism! At that time, it was thought that magnetism would spread throughout a material (like ink in water) until one end was a south pole and the other north, with no possibility of localized regions retaining different levels or directions of magnetization.

In 1894 Valdemar Poulsen demonstrated beyond doubt that localized magnetization in steel wires existed and could be used to record and reproduce electrical signals. This was regarded as quite miraculous at the time, and was indeed revolutionary. Its importance in the history of technology can hardly be overstated, and magnetic recording remains hugely important today. Although tape may be close to dead now, magnetic disks certainly are not. Their replacement by flash memory is under way, but it will not be complete for quite some time (probably not until the next decade I suspect — it is mid-2012 at the time of writing).

The good thing about ferro-magnetism is that it is a robust way of recording electrical signals,

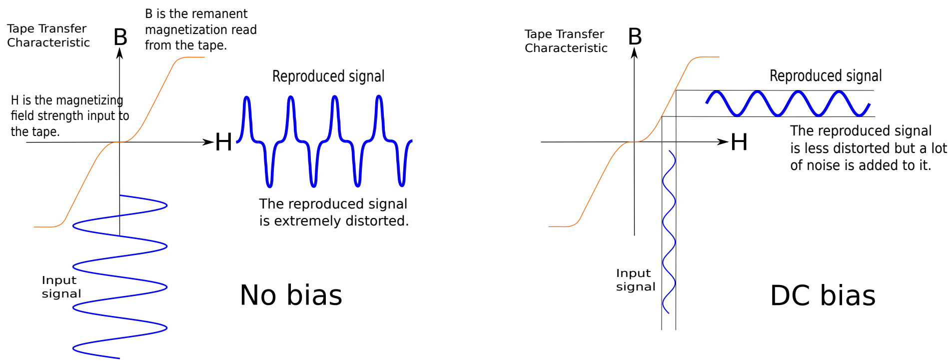

Figure A.1: Tape Transfer Characteristic without Bias and Simple DC Bias

potentially at very high information densities. As far as faithfully recording and reproducing an analog signal goes, however, it leaves a lot to be desired! The problem is that the magnetization retained by the material has a highly non-linear relationship to the applied magnetizing field. Beyond simple non-linearity, the magnetization an external field causes depends greatly on the previous magnetization of the material. If you slowly increase the external field, then start to decrease it, the resulting magnetization for a given field strength on the way down is not the same as it was on the way up! This is known as hysteresis and is a fundamental property of ferromagnetic materials due to the way domains organize themselves under the control of the exchange force.

Magnetism in ferromagnetic materials is complicated. Many of the descriptions that follow are simplified out of necessity (and my ignorance). For practical applications, what we are interested in is the relationship between the applied external field, which we will denote by H and the permanent or remanent magnetization left in the material as a result of that field, which we will denote by B. We will call this relationship the tape transfer characteristic although "tape" might be steel wire in some of what follows. We want the transfer characteristic to be linear, but it is naturally anything but. Bias schemes are all attempts to linearise it.

Figure A.1 (left) shows a typical tape transfer characteristic. Note that this ignores hysteresis, and is only valid if the magnetic material starts in a state of zero net magnetization. We will almost always assume that we start off in this demagnetized state in what follows, and generally ignore hysteresis.

As we can see, there is a dirty great "dead band" in the middle for low applied fields, followed by a fairly (but not very) "linear region", then a 'saturation region' where the magnetization "maxes out" regardless of how strong the applied field gets. If the applied field, H, is a sine wave, the resulting magnetization, B, shows terrible "crossover" distortion. This would be hideous if used to record sound signals. This is the state of things in Poulsen's original experiments and, probably, his 1894/98 apparatus. It could be used to demonstrate that magnetic recording worked, and could maybe be useful for recording Morse code ... but that is about all.

The obvious thing to do is to move the H signal to the linear region by adding a constant DC current to the coil generating the field.

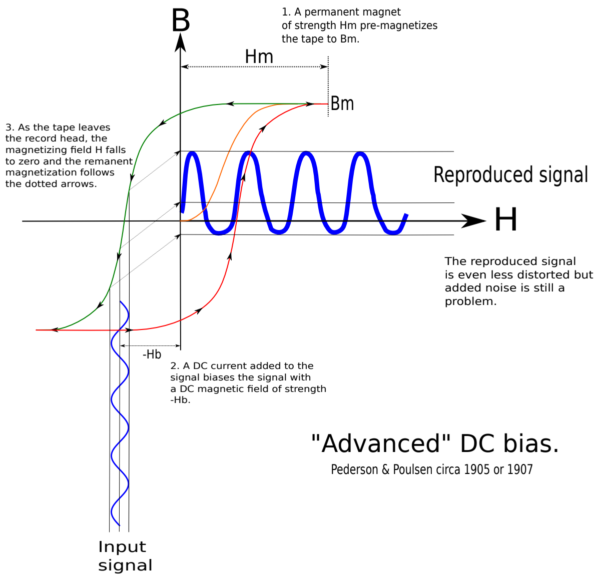

Figure A.2: Better DC Bias

Figure A.1 (right) shows this scheme. This was almost certainly introduced in Poulsen's machines as the 19th century turned in to the 20th. This makes the B signal a more faithful representation of the H input. However, only a small region of the transfer characteristic can be used: H must be small and this worsens the noise performance. It seems that just having a DC H will add noise because the net magnetization is not zero — I don't fully understand why, though. So this is still pretty bad. Magnetic recording would still sound pretty terrible — and terribly faint — at the period this was introduced, especially since there was no electronic amplification available at that time to make the signal louder.

Poulsen and his engineer, Pederson, had another version of DC bias up their sleeve, though. This was introduced in 1905 to 1907.

As shown in Figure A.2, this explicitly uses hysteresis to get a somewhat better result and is a clever improvement on the "simple DC bias" scheme. Noise remains a major problem though, and distortion is still bad ... perhaps 10%. Even with careful development, magnetic recording remained inferior to what could be achieved with disc cutting recording ... until AC bias finally came to the rescue. Probably the best that was achieved with DC bias was something like a 70Hz to 7kHz useful bandwidth with 40 to 45dB signal-to-noise ratio. Remarkably, DC bias was used in dictating machines well in to the 1970's.

A.0.1 AC bias to the rescue.

AC bias has a strange history. The basic physics underlying the process (anhysteretic magnetization) was explored by Steinhaus and Gumlich in Germany in 1915. AC bias for magnetic recording was then independently discovered at least three times.

The first time was in 1921 by Carpenter and Carlson of the U.S. Naval Research labs when they were experimenting with Poulsen *Telegraphon* machines. These were found to have been used in

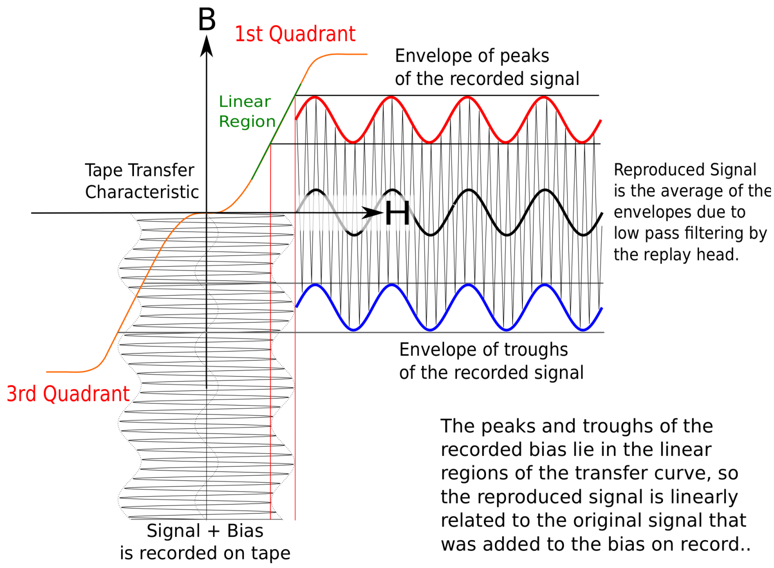

Figure A.3: Conventional Portrayal of the Action of AC Bias

a First World War German espionage scheme to transmit Morse code at very high speeds, which brought them to the attention of the U.S. Navy. AC bias was discovered a second time by Nagai, Sasaki and Endo in Japan around 1938. Neither of these groups seemed to see its potential though. Finally, in 1940, Hans Joachim von Braunmühl and Walter Weber of the German RRG broadcasting service discovered it again (accidentally!) and understood what could be done with it — a massive improvement in performance.

The basic scheme is to generate an AC signal at 5 or more times the maximum frequency that is to be recorded (e.g. 100kHz for the 20kHz audio range) and perhaps 10 times the strength of the signal to be recorded. The audio signal is then simply added to the bias signal. This is not amplitude modulation, but simple superposition.

The standard explanation for how AC bias works is shown in Figure A.3. The bias plus the signal, H, is recorded on the tape with the resulting peaks and troughs in the linear regions of the transfer characteristic. The replay head averages the resulting B field over an area on the tape considerably bigger than the bias wavelength. The result is a clean, linear reproduction of the original signal, with a substantially flat frequency response quite possible over the full audio range and a signal to noise ratio better than 70dB. This is such an improvement over DC bias that it revolutionized magnetic recording. It was now clearly superior to disc cutting — although as we know it actually transformed the recording process for vinyl discs rather than replacing the discs themselves.

So that is that! *Except. . .* There are quite a few deficiencies with this explanation of how AC bias works:

- The bias signal is not recorded faithfully on the tape as shown in the diagram. It is often recoverable from the tape with suitable heads (capable of reproducing its short wavelength), but those clean full amplitude transitions are not recorded. So the averaging process as shown will not work. So why does AC bias succeed in dramatically reducing distortion?

- The sensitivity of the tape (i.e. the B that results from a given H) increases with the strength of the bias field up to a point and then declines. Why?
- The frequency response of tape changes dramatically with the strength of the bias field. At low bias strengths, the HF response is greatly exaggerated and declines as the bias field increases. Why?

All the graphs above showing B plotted against H are based on measurements of large samples of material. To try to answer our outstanding questions, we need to look at the microscopic structure of tape and what happens at that level when we magnetize it and subsequently convert its remanent magnetic field to an electrical signal.

A.0.2 Towards a real understanding of AC bias

A nice explanation for what is going on with AC bias recording is found in this paper:

Magnetic Characteristics of Recording Tapes and the Mechanism of the Recording Process,
J. G. Woodward and E. Della Torre,
11th Annual Meeting of the Audio Engineering Society, October 5th - 9th 1959

and a follow up to that:

Particle Interaction in Magnetic Recording Tapes,
J. G. Woodward and E. Della Torre,
J. App. Physics, **31**, 1, 1960

This work really starts to get to the heart of the matter. Unfortunately, neither paper is freely available, but the AES one is well worth the $20 it costs to access it. What follows was inspired by these papers.

To understand how AC bias really works, we need to look at what tape is actually made of. Figure A.4 shows some of the critical components. We have a very large number of very small particles, often of gamma ferric oxide. These particles are cigar shaped — long and relatively thin — and typically they are around 0.5μm in length and 0.1μm in diameter. They are embedded in a non-magnetic, plastic binder. They are closely packed (about 50% of the volume is occupied by the particles) but separate. The particles are "lined up" when the tape is made so that their long axis lies in the direction of the length of the tape within around $\pm$30 degrees. There will be a distribution of particle sizes: some will be smaller than average and some bigger.

Each of these particles behaves as a single magnetic domain. Each, in practice, can be magnetized in only one of two ways: North-South or South-North. That is, either there is a North pole at one of the sharp ends and a South pole at the other, or vice versa. Lets call this magnetic orientation the magnetic polarity of the particle, or m, with a value of either $+1$ (say for N-S) or -1 (S-N).

The strength of the magnetic field of each particle is:

$$mc \tag{A.1}$$

where c is the "size" (which we will take to be the length) of the particle.

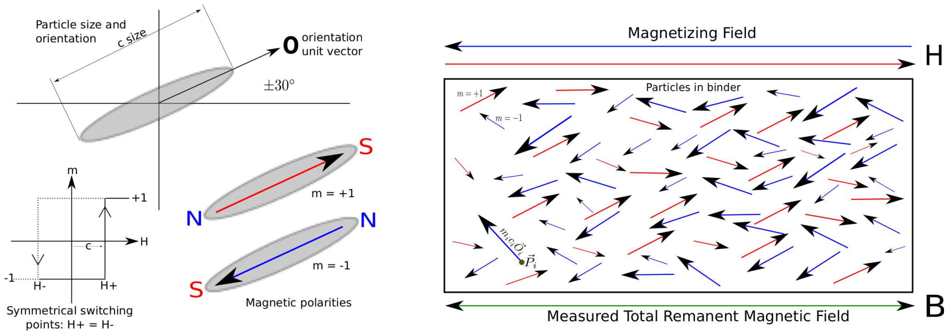

Figure A.4: Magnetic Particles and Magnetic Tape

Suppose there is an external field, H, which can be represented as a vector in the $\vec{X}$ direction. We'll use H to denote the strength of this field. H may be positive or negative. Let's think about a short piece of tape, with its long dimension also in the $\vec{X}$ direction, exposed to H. Figure A.4 (right) is a drawing of this highly idealized and 2 dimensional piece of tape. (We are looking down on its surface, ignoring its thickness.)

Suppose we can also measure the magnetization, B, of this short piece of tape, making the measurement along the $\vec{X}$ direction. With this arrangement, we only need to worry about the $\vec{X}$ component of the various vectors that are involved in most cases.

$$B = \sum_{i=1}^{n} m_i c_i \vec{O}_{i_x} \tag{A.2}$$

That is, the magnetization we measure for our small region of tape is just the sum of the magnetic fields of the particles acting in the direction we are measuring. This is the "replay head" integrating the magnetic field it "sees" in a real system. There the details are more complicated, but the overall principle is the same.

The erased state of the tape is one in which there is a completely random assignment of magnetic polarities to particles, with equal numbers of $m = +1$ and $m = -1$ states which will sum up to a measured B of close to zero. The actual B will fluctuate about zero for different tape segments and the granular magnetic structure of the tape is what is responsible for the noise of erased tape.

For each particle, there will be a value of H which will switch it from N-S $(m = +1)$ to S-N $(m = -1)$ magnetic polarity.

Considered individually, with its long axis in the direction of H, every particle will have a symmetric hysteresis curve. If $H = 0.6$ switches it from $m = -1$ to $m = +1$, then $H = -0.6$ will switch it from $m = +1$ to $m = -1$. The value of H that does this switching we will assume is dependent only on the size of the particle, c.

The actual H value that will switch the polarity of a given single particle in the binder from $+1$ to -1 or vice versa will also depend on the particle's geometric orientation $\vec{O}$. The switching values of H will still be symmetric for each particle though.

A given particle will be switched when H "overcomes" the magnetic field of the particle itself. This

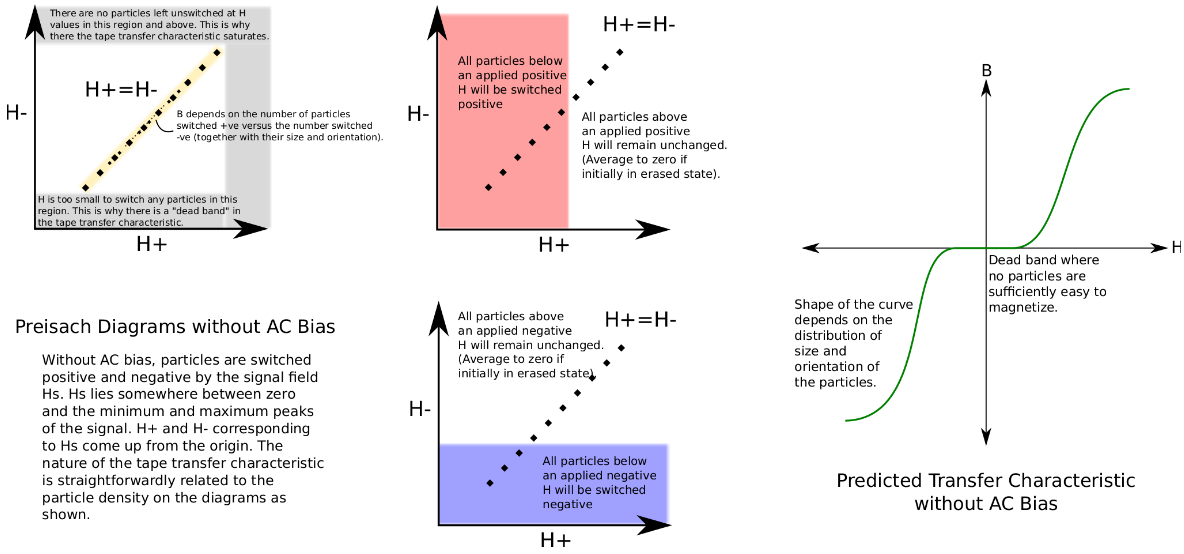

Figure A.5: Preisach Diagrams without AC Bias and Predicted Transfer Characteristic

field has a strength mc and is oriented along $\vec{O}$. The polarity m will switch to the polarity of H when the magnitude of the component of H acting in the direction of O equals or exceeds $|mc|$.

$$\left|\vec{O} \bullet \vec{H}\right| = |mc| \tag{A.3}$$

If we plot the H that switches a particle to $m = +1$, H_+, against the H that switches it to $m = -1$, H_-, we get what is called a Preisach diagram. (Actually, it seems that H_+ is always plotted against $-H_-$, so the plot lies predominantly in the first quadrant. This is a little confusing, but we follow this convention here).

From what we have said so far, we would expect all the points on such a plot to lie on the $X = Y$ line.

For a given particle, i, we would expect:

$$H_+ = +\frac{c_i}{\vec{O}_{i_x}} \tag{A.4}$$

$$H_- = -\frac{c_i}{\vec{O}_{i_x}} \tag{A.5}$$

where $\vec{O}_{i_x}$ is the x component of the $\vec{O}$ orientation unit vector (along the long axis of the particle), and c_i is its size.

Let's look at the Preisach diagram for this case (Figure A.5) and see what it implies if we operate without AC bias.

We can see how our microscopic picture of what is happening in the tape corresponds to its macroscopic measured transfer characteristic.

What happens with AC bias? In this, the signal, H_s, is added to a much stronger bias, H_b, and

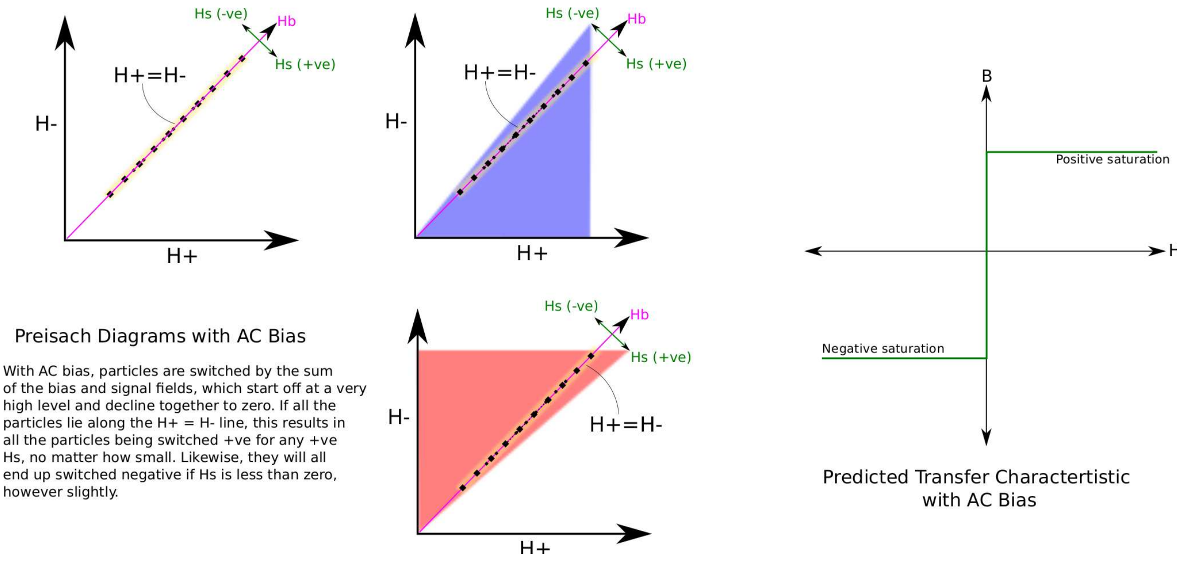

Figure A.6: Preisach Diagrams with AC Bias and Predicted Transfer Characteristic

the two decay away together to zero as the tape element moves away from the record head. This leads to the very unfortunate result shown in Figure A.6.

AC bias just does not work! The predicted B versus H curve switches from saturated $-B$ to saturated $+B$ as H goes though zero! This is obviously wrong.

It is possible to plot a Preisach diagram for a real tape and fortunately it turns out that all the points do not lie on the $X = Y$ line. This is what Woodward and Della Torre did. Instead, there is a cloud of points distributed symmetrically about that line (as if reflected in the $X = Y$ line).

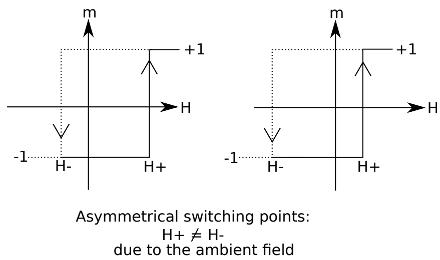

Figure A.7: Switching Points for Two Magnetic Particles in an Ambient Field

The reason for this is that the particles, being magnetized one way or the other, generate a magnetic field of their own, which I'll call the ambient field. The switching points of a given particle are now shifted away from symmetry by the strength and direction of the ambient field at the position of that particle. Taking this in to account:

$$H_+ = +\frac{c_i}{\vec{O}_{i_x}} + a_{i_x} \tag{A.6}$$

$$H_- = -\frac{c_i}{\vec{O}_{i_x}} + a_{i_x} \tag{A.7}$$

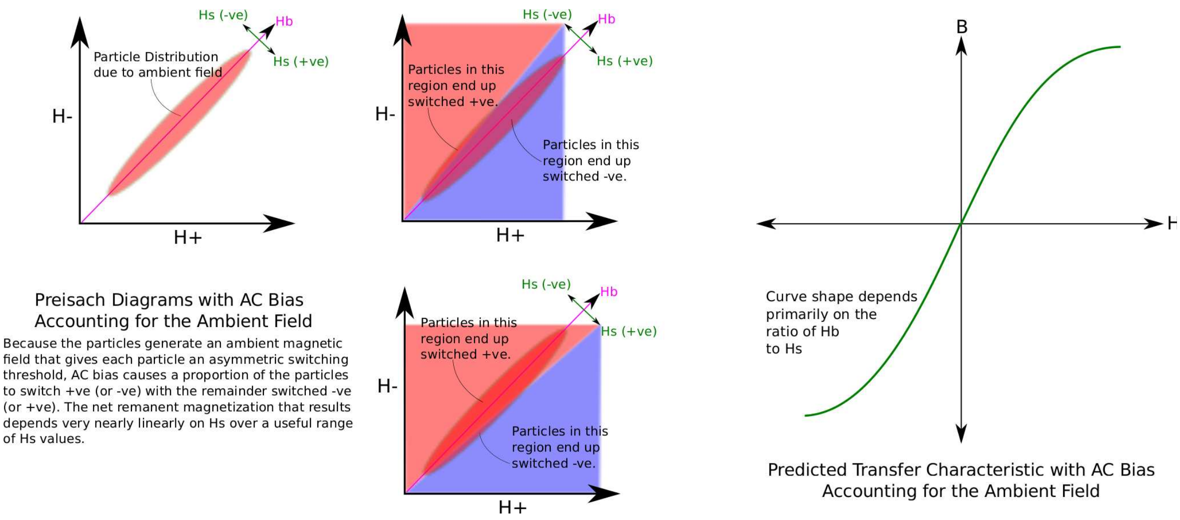

Figure A.8: Preisach Diagrams with AC Bias and an Ambient Field

where a_{i_x} is the x component of the ambient field.

For a given arrangement of n particles, with each particle located at $\vec{p}_j$, with a polarity m_j, orientation $\vec{O}_j$ and size c_j, the ambient field experienced by particle i, a_i, at its position, p_i will be:

$$\vec{a}_i = \sum_{j=1, j \neq i}^{n} \frac{m_j c_j \vec{O}_j}{|\vec{p}_i - \vec{p}_j|^2} \tag{A.8}$$

This ambient field shifts the switching points of each individual particle. They no longer switch negative at the same H_- as the H_+ for which they switch positive, as shown in Figure A.7. The particle population is no longer confined to the $H_+ = H_-$ line. It spreads out along the H_s direction. The exact shape of the distribution depends on the details of how close the particles are, how much they tend to clump together, the size distribution and so forth. The shape is critical in determining the performance characteristics of the tape.

The outcome of this is that half cycles of the combined $H_s + H_b$ field switch the particle population first positive and then negative, with fewer and fewer of them being switched as $H_s + H_b$ declines to zero. The population ends up divided in to two groups: positive and negative. If $H_s = 0$, the population is evenly divided down the $H_+ = H_-$ line. If $H_s > 0$, however, more end up positive than negative, and vice versa if $H_s < 0$. This is shown on the left of Figure A.8.

The relationship between H_s and the net remanent magnetization ends up being very nearly linear over a good range of H_s, as shown on the right in Figure A.8. This is exactly what is wanted of course!

Note that this linearity (and the magnitude of the reproduced signal) is dependent on the difference between the number of particles switched positive and the number switched negative in the region sensed by the reproduce head. Analog magnetic recording with AC bias is very much a discrete process at its heart.

A.0.3 Simulating the AC bias process in software

Now, it seems that we might be able to do a direct, naive, simulation of such a system of particles and see what happens ... This is what the program `magsimo` does in 2D in a very straightforward (simple minded, even) way.

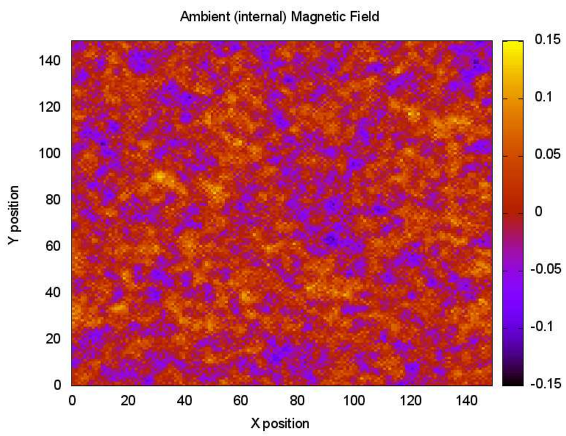

Figure A.9: Simulated Ambient Field

We start with a grid of 150 $\times$ 150 particles. These are arranged on a regular grid then "jittered" so their positions are somewhat random. They are assigned a random orientation vector within $\pm$30 degrees of horizontal. They each also get a random size and a random initial magnetic polarity. The assembly as a whole has (approximately) zero net magnetization. From this we can calculate the ambient field, an example of which is shown in Figure A.9.

Given the ambient field, we can then find the H_+ and H_- for every particle. An example of that is shown in Figure A.10.

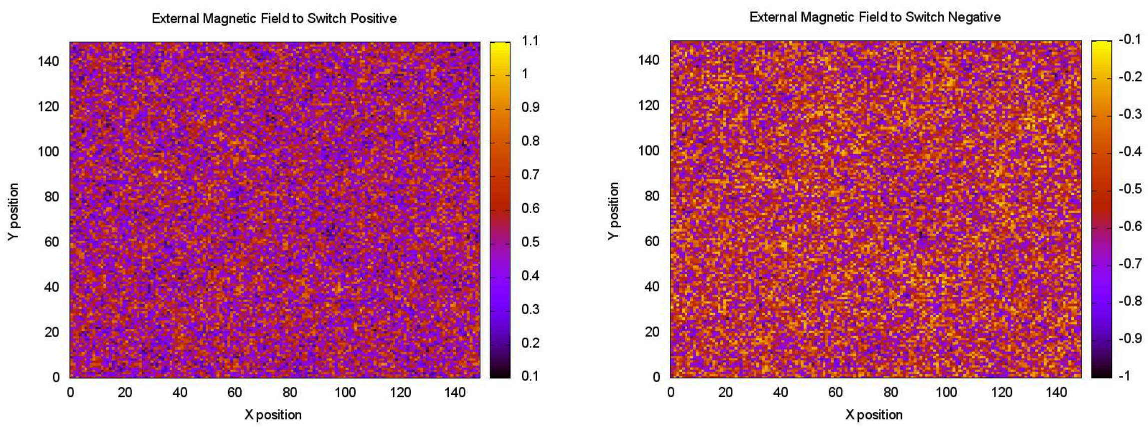

Figure A.10: Positive and Negative Switching Field for each Particle

Now we have that information, we are in a position to plot a Preisach diagram (Figure A.11, left) for our simulated tape. This is, as expected, a fair approximation to a distribution centred on the $X = Y$ line and roughly symmetric in reflection about that line.

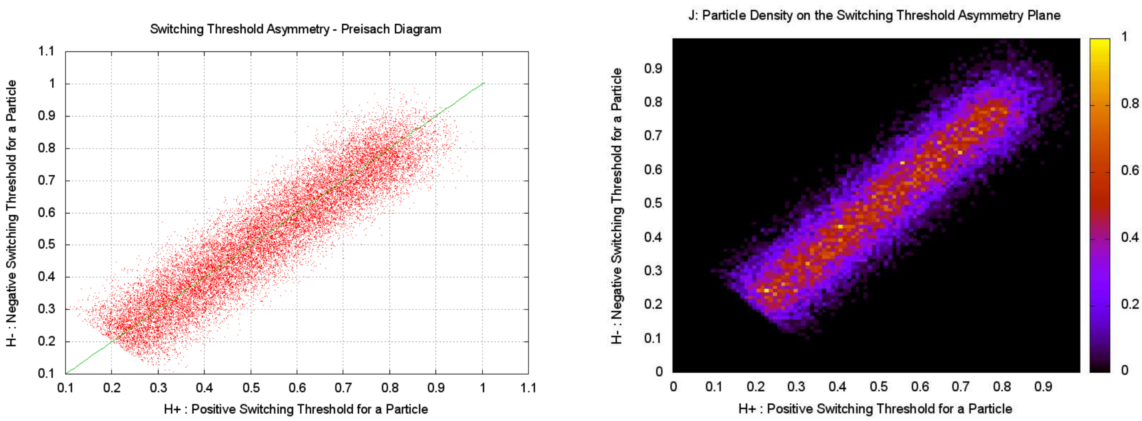

Figure A.11: Preisach Diagram and J-function for the Simulated Particles

If we count the number of particles per unit area on the Preisach diagram, we get what is known as the J function (Figure A.11, right). We won't actually make much use of this here, but it tells you how many particles will switch at a particular pair of H_+, H_- values: $J(H_+, H_-)$. We don't have very many particles in our simulation, so it is a bit bumpy, but this is what can actually be measured for a real tape — where there are so many particles involved that the function will be smooth.

With AC bias, the H field at the recording head which is the sum of the bias, H_b, and signal, H_s, is very strong and switches between $H_+ = 1$ and $H_- = 1$. An element of tape (which we are simulating here) will have all its particles switched to $m = +1$, then to $m = -1$. That is, the positive and negative excursions of H cover the whole Preisach diagram.

As the element moves away from the recording head, the H field declines to zero — both H_b and H_s die away together. First the H_+, then H_- field "sweep" a progressively smaller region of the Preisach diagram. If there is no signal, the sweep is symmetrical and in the end, equal numbers of particles are switched positive as are switched negative. The process is shown in Figure A.12 for the case of $H_s = 0.0$ and $H_s = 0.1$ (with $H_b = 1.0$).

The process is clearer if shown as an animated sequence, but that isn't possible in a printed document!

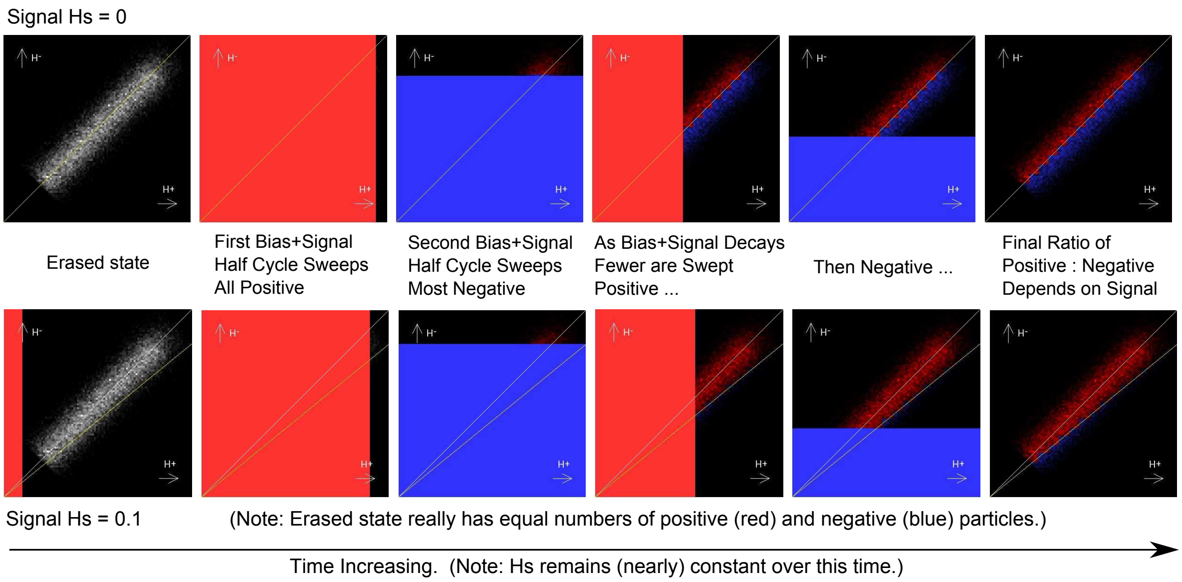

Figure A.12: The AC Bias Process in Action

The end result for $H_s = 0.0$ is a stepped approximation to the $X = Y$ line on the Preisach diagram or J function. This line separates the particles that end up positive from those that end up negative and results in a net magnetization, M, of zero.

But if the signal is greater than zero, the H field sweeps fewer particles negative than it sweeps positive, resulting in a positive net magnetization. There is now a stepped approximation to a line of slope:

$$m = \frac{H_b - H_s}{H_b + H_s} \tag{A.9}$$

on the Preisach diagram separating the particles that end up positive from those that end up negative.

If we are successfully simulating the AC bias process, the net magnetization should be linear over some range of H_s.

Figure A.13 (left) shows what the simulation predicts with zero bias. Well, that looks pretty much as we would expect!

What happens with "full" AC bias? Figure A.13 (right) shows that, and it looks pretty much exactly what we would hope to see for AC bias, with a good linear section and considerably greater sensitivity (maximum slope of the transfer characteristic) than without AC bias.

Let's push our luck a bit further and see what happens as we change H_b, increasing from zero. Ideally, we would see distortion fall and sensitivity increase to a peak, then the sensitivity should start to fall and distortion reduce further. The results are shown in Figures A.14 and A.15.

For such a simple minded simulation, that is very satisfactory. This is much more like how AC bias recording really works!

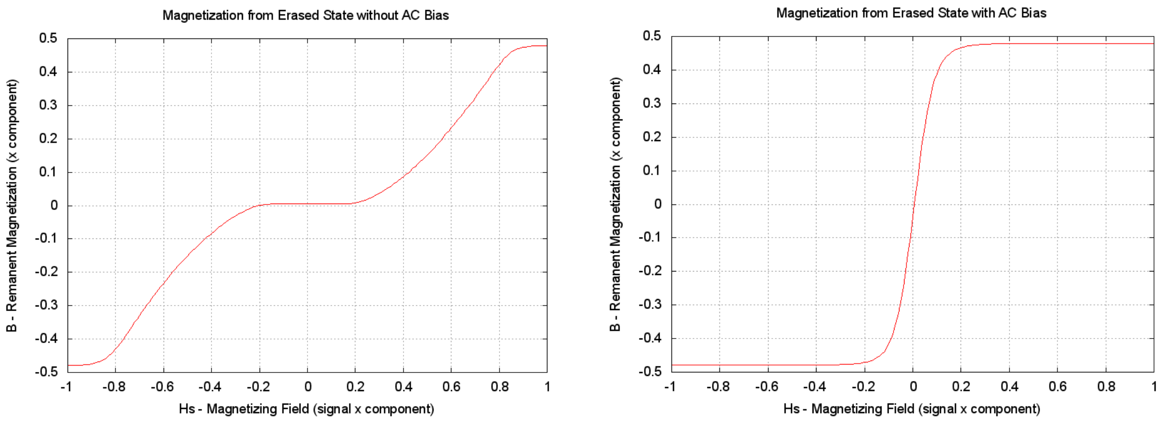

Figure A.13: Simulated Transfer Functions Without and With AC Bias

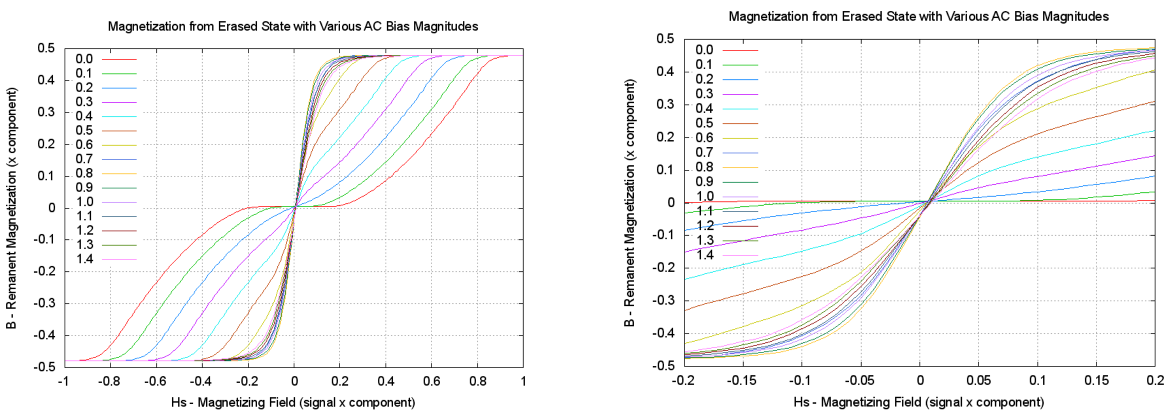

Figure A.14: Simulated Transfer Functions For Various AC Bias Levels

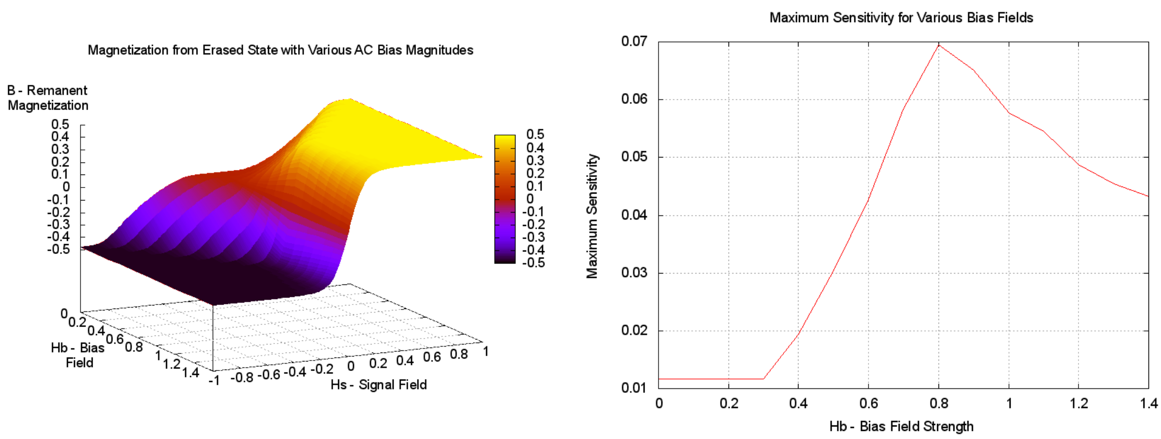

Figure A.15: Sensitivity for Various AC Bias Levels

However. . . This is pretty much as far as I have been able to take the reproduction of AC bias behaviour with this simple simulation. We have succeeded in reproducing two of the effects not fully explained by the "simple explanation" given in Section A.0.1.

- How AC bias dramatically reduces distortion even though the bias waveform is not faithfully recorded.
- How the sensitivity of the tape increases with the strength of the bias field up to a point and then declines.

I can't actually think of a good way of making the simulation reproduce the third effect of AC bias:

- The frequency response of tape changes dramatically with the strength of the bias field. At low bias strengths, the HF response is greatly exaggerated and declines as the bias field increases.

Woodward and Della Torre did manage to do this using an analysis of the J-functions they measured for two real tapes, but I can't really see how to generalize that and implement it in software.

Furthermore. . . There is actually a problem with the Woodward and Della Torre model which was noted by the J. App. Physics reviewers. As the external field "flips" the magnetization of particles the ambient field (which affects when particles "flip") will change. This means that it isn't possible to assign a fixed negative and positive switching field value to each particle in the way that `magsimo` (and, effectively, Woodward and Della Torre's paper) does. In fact, `magsimo` originally tried to iterate until it found a stable ambient field. . . but unless the particles were spaced far apart (or an equivalent) the ambient field never stabilized. Particles got in to stable patterns of oscillation, much like cells in Conway's *Game of Life*. The argument was that, at least for real tapes, the whole system was statistically stable and behaved as if you could assign fixed switching fields to individual particles, even though you can't do that. I'm not sure if this issue was ever resolved, although real tape does behave as if that assertion were true. Sort of.

In the 1970's there were many numerical simulations of magnetic recording processes, including AC bias, and some of them became very complex. Just how accurate and useful they were seems to be in some doubt (judging by comments on "self-consistent models" in Chapter 6 of "The Foundations of Magnetic Recording" by John C. Mallinson[1]).

Other models of the recording process include the Bauer-Mee Bubble Model which is concerned with how magnetisation takes place through the thickness of the tape. There is a very interesting thesis[2] by W. J. W. Kitzen from 1978 which applies the Neel and Stoner-Wohlfarth fundamental physical theories of magnetization to magnetic tape and develops sophisticated simulation software based on them.

Well, all this is just ancient history now. But it really is very complicated indeed. Maybe one advantage of digital audio is that it is so much simpler!

[1] ISBN 0-12-466626-4. Available via "print-on-demand" from Elsevier for about $100, or second-hand via Abe Books for less than $20. This is an excellent book, in my opinion.

[2] *Magnetic Interaction in Recording Media*, W. J. W. Kitzen, Eindhoven University of Technology, M.Sc. Thesis ET-19-78