Amplitude modulation of noise from wind turbines due to propagation through the atmosphere

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ABSTRACT

At distances of several hundred meters and more, the noise from wind turbines is sometimes perceived as a "thumping" sound, with an amplitude modulation of the sound pressure levels that corresponds to the frequency of the rotation of the turbine. While some of these modulations can be part of the emission, being caused by the turbine itself, such amplitude modulations can also be caused by the propagation of the sound through the atmosphere. The mechanism for this is presented, as well as atmospheric conditions that will result in strong amplitude modulations at long distances. A simple constant radius ray tracing model is used, and its limitations as well as the validity of the general argument are discussed.

1. INTRODUCTION

Sometimes "swishing" or "thumping" noises from wind turbines can be heard at distances of several hundred meters and more. These sounds are low frequency amplitude modulations that are strongly correlated to the rotor blades moving, sometimes attributed by annoyed neighbors to the blades passing the supporting structure of the wind turbine.

The processes that lead to these amplitude modulations are not fully understood. There have been studies that attribute the amplitude modulations to directivity of the emission from the blades, or to height dependent emissions from the blades due to height dependent wind speeds [1,2]. Any of these approaches does not in itself explain why the amplitude modulations sometimes occur, and sometimes don't, but a dependency of the likelihood of amplitude modulations on atmospheric conditions has been observed [3].

In this paper, we completely neglect directivity or height dependence of the source, and look into a process that causes amplitude modulations during the transmission through the atmosphere.

2. DIFFRACTION IN THE ATMOSPHERE

The effective sound speed in the atmosphere is made up of the sum of the speed of sound and the wind. While wind speed almost always increases with height, the speed of sound usually decreases with height, but can also increase with height in inversion situations. In any case, in the context of sound emitted from wind turbines it is safe to assume that downwind the increase of wind speed with height outweighs a decrease of sound speed with height, so that the effective sound speed in the down wind direction increases with height.

Since sound follows Fermat's principle and follows the quickest path between two points, effective sound speed going up with height results in downward diffraction. In this paper, the paths of the sound are called rays, and they are the lines the energy flow follows. The diffraction due to the gradient in the effective sound speed results in rays being bent with a radius

$$r \approx \frac{c_{eff}}{\partial c_{eff}/\partial z} \tag{1}$$

with c_{eff} being the sum of the speed of sound and the proportion of the wind in the direction of propagation, z the height, and $\partial c_{eff}/\partial z$ the height dependent gradient of the effective sound speed. For simplicies sake, the influence of the vertical angle of the rays on the radius is neglected. This is the most simple case of a constant radius ray model.

Figure 1shows rays going from a source at 100m height to a receiver at 1000m distance and 10m height. The radius from diffraction is chosen to be 1000m, which corresponds to a gradient of the effective sound speed of 0.34 (m/s)/m. The height of the receiver is chosen so the separate rays are easier to see than they were if it was set to for example 2m.

For the same conditions, but with the source at 65m height, Figure 2 shows the rays going from the source to the same receiver at 1000m distance and 10m height. While the conditions in Figure 1 result in a direct ray and one ray with a ground reflection, the lower source height in Figure 2 results in two additional rays with a ground reflection.
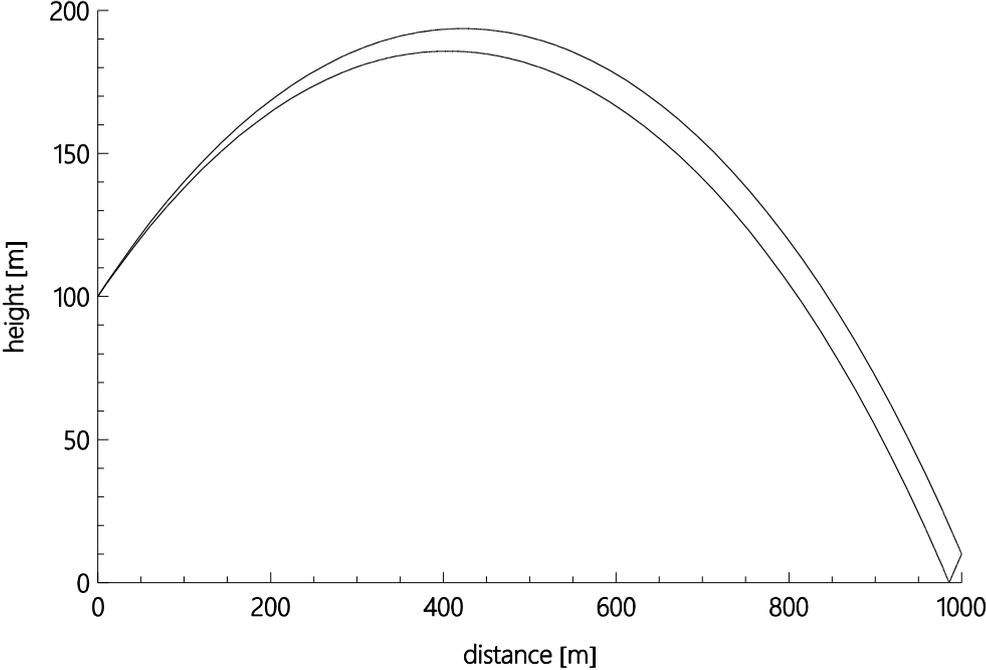
Figure 1 – Rays between source at 100m height, and receiver at 10m height and 1000m distance
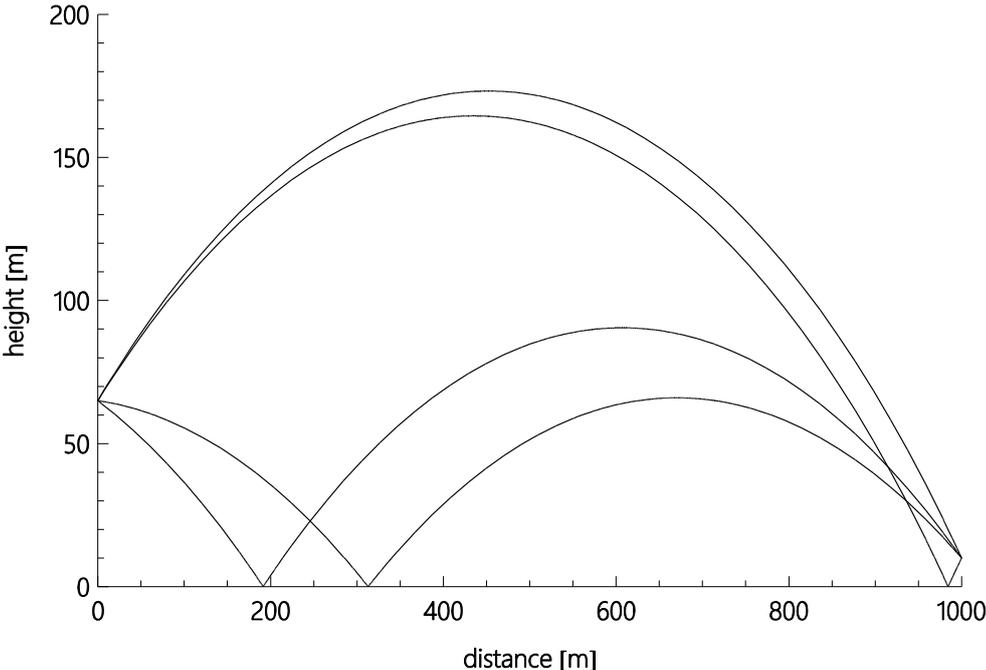
Figure 2 – Rays between source at 65m height, and receiver at 10m height and 1000m distance

So by lowering the source height, the number of rays getting to the receiver changed, and went up from 2 to 4. On anything but a strongly absorbing ground, additional rays result in a significant change in the sound pressure level at the receiver.

In the context of wind turbines, this would indicate sound pressure going up every time the source, i.e. a rotor blade, is lower than a certain height, resulting in an amplitude modulation.

Figure 3 shows the areas for the receiver in which there are two or four rays between source and receiver for different source heights. As the source height is decreased, the area with four rays moves down and closer to the source.

3. EFFECT ON LEVELS

For simplicities sake, the ground reflection is assumed as lossless. And since the sound from wind turbines is very noisy, and again mostly for simplicities sake, the addition of the signals is taken to be incoherent. So going from one to two rays gives +3 dB, and going from two to four rays gives another +3 dB. So in this very simple approach, a jump by +3 dB is expected when the source goes into the height range with the two additional rays. This effect of addition rays at the receiver can be described in terms of $-A_{gr}$ as it is in ISO9613-2.

However, due to the diffraction the local levels look a bit different. The rays are the lines of energy flow, portions of the energy flow are confined between those lines. If distance between the lines increases with distance from the source, the energy flow is diluted, and the level drops. For straight lines for example, the distance between adjacent lines is directly proportional to the distance from the source. With the rays, i.e. energy flow lines, being bent, this no longer holds true. In addition to adding up the contributions of individual rays, we also take into account the difference between the actual energy flow density for each ray and what would be expected without diffraction, i.e. with simple geometric damping.
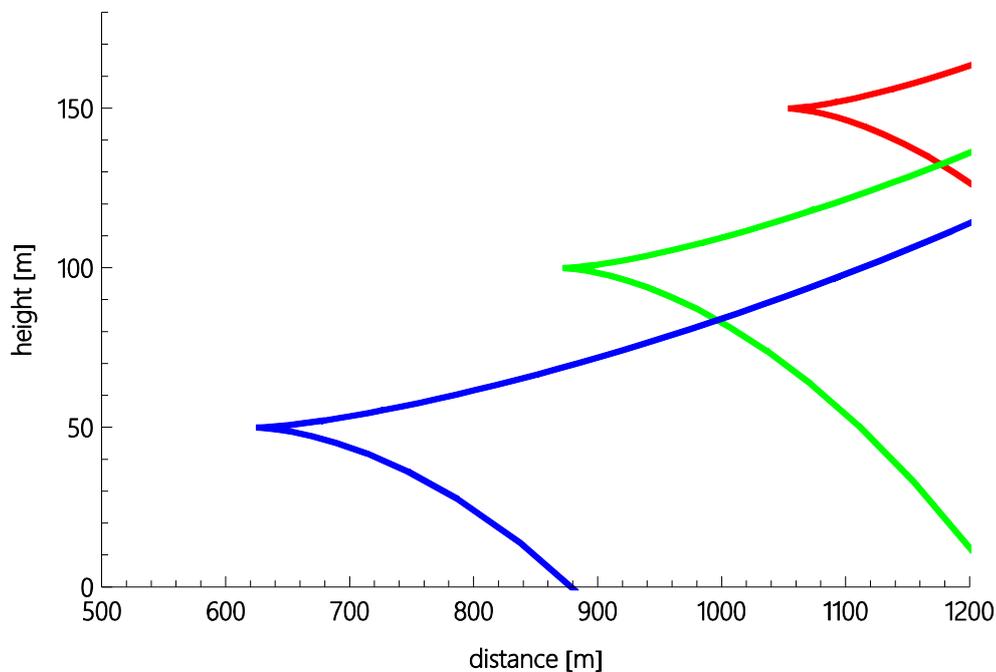
Figure 3 – The (caustic) border lines between the area with two rays to the left, and four rays to the right.

Diffraction radius is 1000m, source height is 50m (blue), 100m (green), 150m (red)

Figure 4 shows the actual effect of the reflected rays on the level at 1000m distance, with a radius of 1000m and the receiver at 10m height versus the height of the source. In the "two rays only" region, $-A_{gr}$ is close to the 3 dB that would be expected without diffraction.

In the range with four rays, away from the boundary between the two regions, $-A_{gr}$ is close to the 6 dB that would be expected if diffraction was neglected in the calculation of the energy flow. However, as the boundary is approached from the region with four rays, the levels diverge.

Such a divergence is called a caustic.

3.1 Caustic

The divergence shown in Figure 4 is a result of looking at the energy flow being squeezed in between the geometric rays. This approach is only valid as long as the Eikonal approximation is good, which requires a smooth and slow change in intensity. This certainly does not apply if there is a diverging level and a jump to finite level.

Using a local solution to the wave equation, the level offset vs. height can still be determined [4,5], and instead of a divergence, a frequency dependent solution based on Airy functions is found. Figure 5 shows results for different frequencies. The divergence is replaced by smoother functions with a finite peak. The periodically rising and falling levels are a result of interference between the rays.

3.2 Levels for a noisy source

Without going into detail for the source, the sound emitted from wind turbines is certainly noisy. Figure 6 shows the level offset for white noise band-limited to 50 to 400 Hz. Some small interference patterns can still be seen, and even though the function is smooth and finite, there still is a significant peak. As the source goes down by 20m, by reaching the peak, the level goes up by about 12 dB.

This is with a hard ground, but even if there was some absorption from the ground, a significant peak would still be seen.
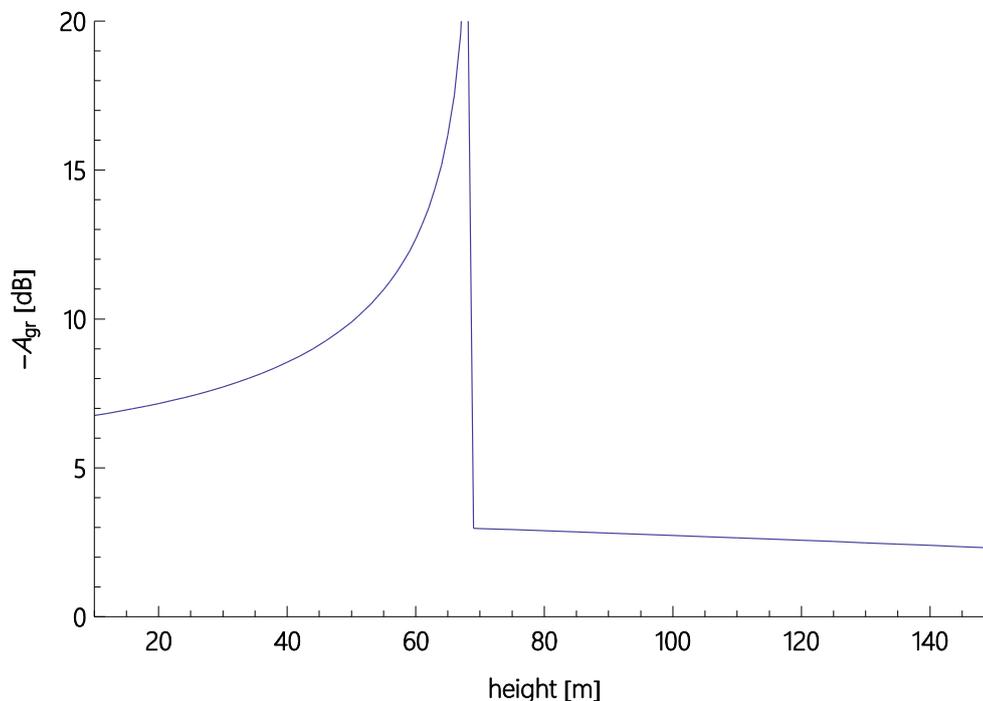
Figure 4 – The level offset A_{gr} at 1000m distance vs source height. Geometric solution.
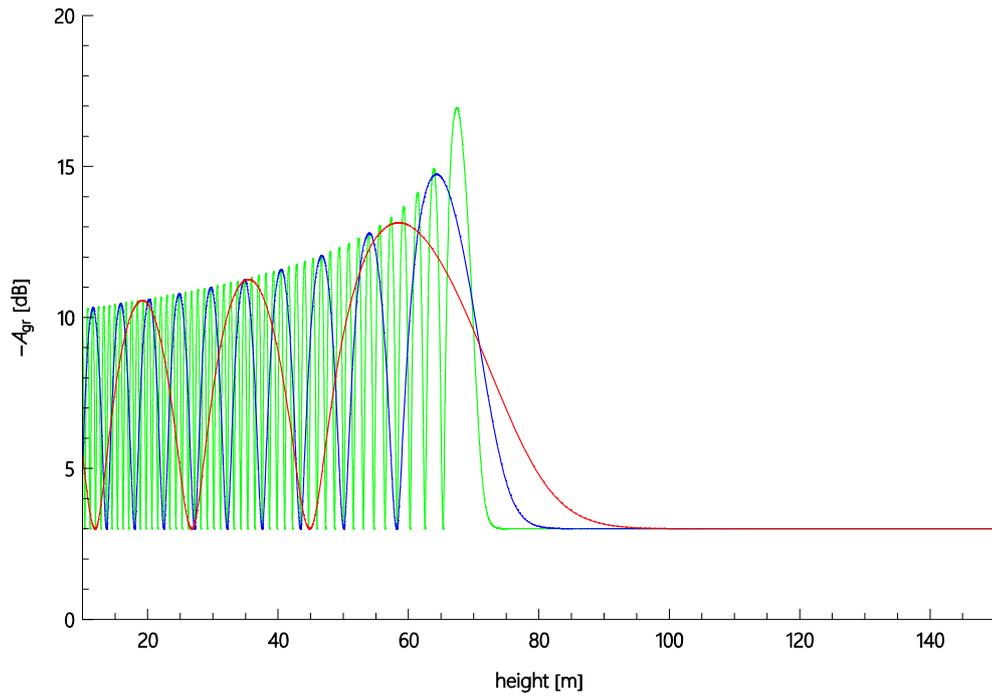
Figure 5- A_{gr} at 1000m vs source height, for 500 Hz (green), 100 Hz (blue), 30 Hz (red)
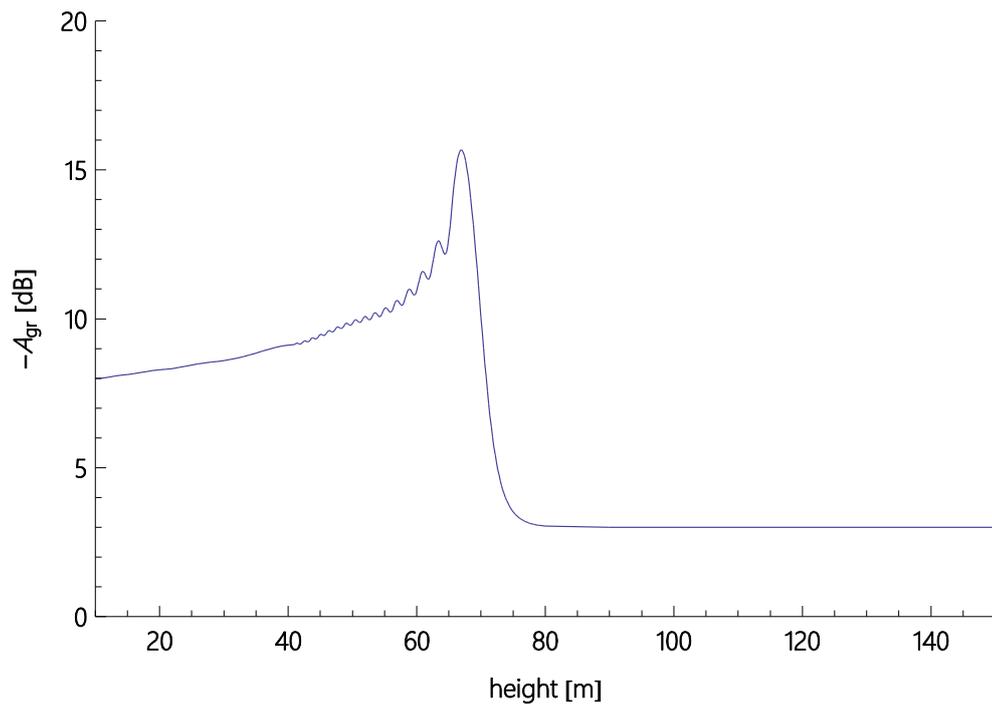
Figure 6 - A_{gr} at 1000m vs source height, with a band limited white noise spectrum from 50 to 400 Hz

4. APPLICABILITY AND LIMITATIONS

4.1 The model

The results shown in this paper are based on circular rays. All rays have the same radius everywhere.

Doing this does not exactly apply to any type of atmospheric profile. Even if there is no wind, there is a small influence of the angle of the rays on the radius. And with wind, there are more height dependent changes in the radius of the rays. But with any linear speed profile, a constant radius is still

a fairly good approximation.

The assumption of constant radiuses is made to keep calculations simple, and to not have to rely on numerical simulations. More detailed or better models will show different results in detail, but the basic effects are the same. There will be regions with additional rays getting to the receiver, and the basic shape of these regions will be similar to those in Figure 3. There will be caustics between these regions, and they will always result in a peak when crossing the border between the regions.

4.2   The atmospheric profile

The examples shown are all with a 1000m diffraction radius, which corresponds to a gradient of the effective sound speed of 0.34 (m/s)/m. Figure 7 shows the caustic border lines for different radiuses, and how they are moved to further distances with increasing radius.

For the effect discussed in this paper to be relevant, it has to happen at distances with still relevant levels, so a fairly small radius is required, implying gradients in the range of 0.3 (m/s)/m and more. For heights up to 10m that is a reasonable and very common assumption. Looking at wind turbines, that kind of gradient at 100m height is unlikely under normal operating conditions.

The simplifications in this paper imply a fairly constant gradient in wind and sound speed, which is not to be expected at heights up to 100m. It could be argued that the critical part of the diffraction happens at lower heights, but it seems unlikely to find gradients of 0.3 to 0.5 (m/s)/m under operating conditions at heights between 10m and 50m.

The above applies to an unperturbed atmosphere. However, the wind field downwind from a wind turbine is perturbed. This perturbation may result in effective gradients leading to the presented result.

5.   CONCLUSIONS

Using a very simplified model based on rays with a constant diffraction radius, a process resulting in amplitude modulations for sources moving up and down is presented. These amplitude modulations are not due to properties of the source, other than it moving up and down, but due to the propagation through the atmosphere.

6.   FUTURE RESEARCH

The purpose of this paper is to point out a basic mechanism. To do this, a very simple model with circular rays with constant radius is used. This implies a constant gradient of the effective sound speed, which is not a good assumption for the height range encountered with wind turbines.
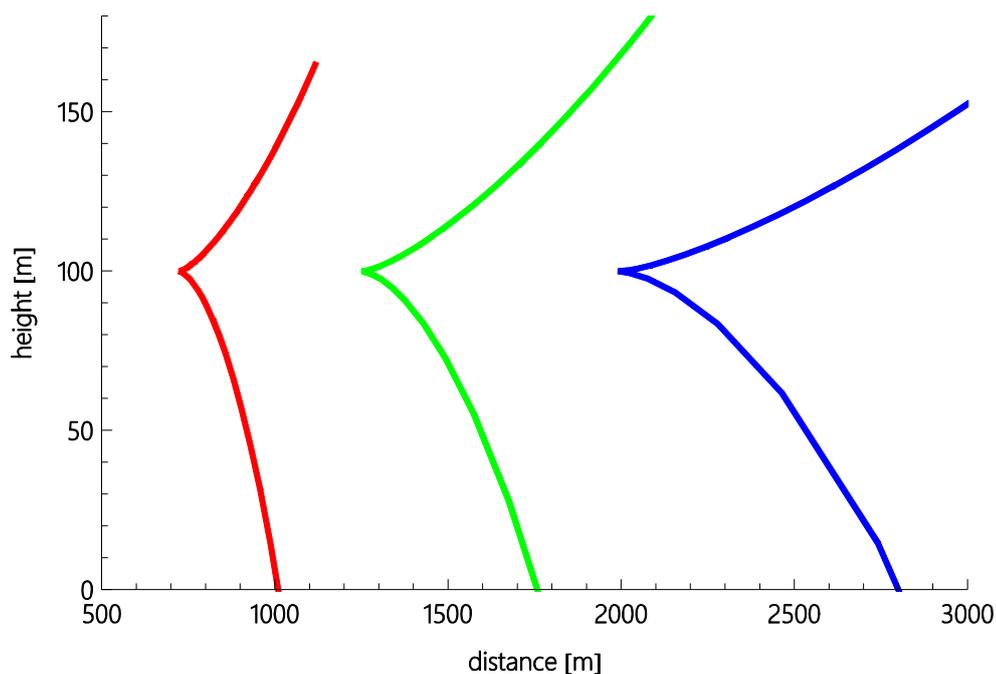
Figure 7 - The (caustic) border lines between the area with two rays to the left, and four rays to the right.

Source at 100m, diffraction radius is 5000m (blue), 200m (green) and 700m (red)

A more detailed model, that can probably only be solved numerically, should be used to study the effect of realistic atmospheric profiles.

And it should be checked if the perturbed wind field downwind from the wind turbines can result in increased gradients that lead to the process discussed in this paper in ranges between 500m and 1000m distance.

The peak that occurs when the source crosses the border to the lower region is fairly sharp. Amplitude modulations should not just show a modulation with three times the rotational frequency of the wind turbine, but under the right circumstances they should actually show two peaks in the modulation. This may require using a time filter shorter than 100ms when studying the amplitude modulation.

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