# Optimized Amplitude Modulated Multi-Band RF pulses

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## Introduction

Multi-Band RF pulses[1] require more peak RF power to produce a given flip angle than single band equivalents. This can severely limit the achievable multi-band factor (MBF; number of simultaneously excited slices). If all slices are excited with the same phase the peak pulse amplitude scales with MBF

i.e. $b_{max}$ = MBF

Where $b_{max}$ = max. amplitude relative to single-band pulse of same flip angle.

Wong[2] showed that optimizing the phase of each slice can result in much lower $b_{max}$, approaching theoretical minimum $b_{max}=\sqrt{MBF}$. This approach has been combined with time-shifting to further reduce the peak amplitude[3,4].

The resulting MB-RF pulses have rapid modulation in both amplitude and phase. Accurate reproduction of this modulation can be problematic. Faithful reproduction of rapid phase modulation can be more error prone than amplitude modulation, especially on systems requiring frequency rather than phase modulation to be defined by the pulse designer.

## Goal

To compute optimal phase offsets to produce **amplitude modulated** MB-RF pulses that minimize $b_{max}$.

## Methods

The modulation function b(t) required to produce slices at locations $x_j$ with gradient G is given by:

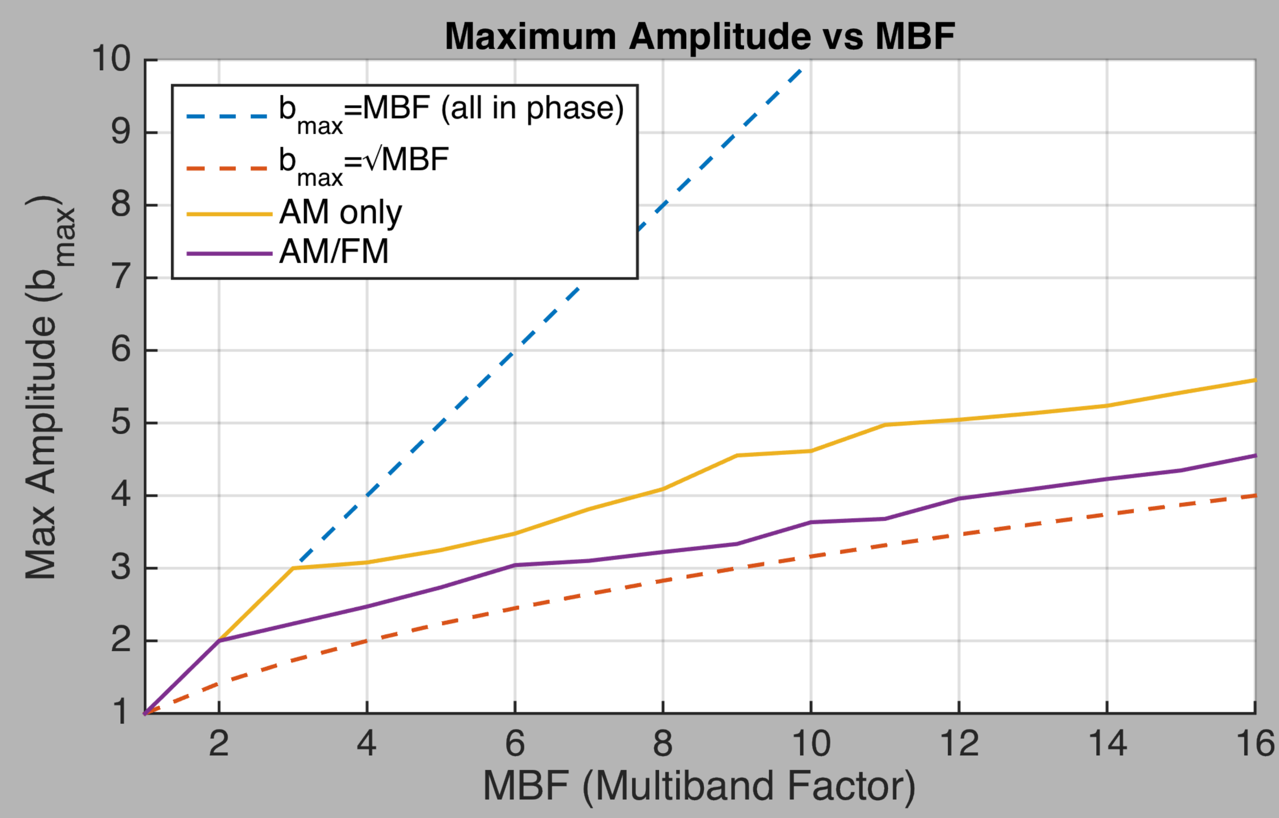
$$b(t) = \sum_j^{MBF} \exp\{i(\gamma G x_j t + \phi_j)\}$$

Phase offsets $\varphi_j$ are to be optimized so as to **minimize** $b_{max}$=max{b(t)}.

AM only pulses are achieved if we obtain real valued b(t). This can be achieved if $\varphi_j$ have conjugate symmetry

| MBF | AM only pulses: optimal slice phase offsets/deg | | | | | | | | | | | | | | | | AM only properties | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | $b_{max}$ | %MBF | %AMFM |
| 4 | 0 | 180 | 180 | 0 | - | - | - | - | - | - | - | - | - | - | - | - | 3.08 | 76 | 80 |
| 5 | 0 | 0 | 180 | 0 | 0 | - | - | - | - | - | - | - | - | - | - | - | 3.25 | 64 | 84 |
| 6 | 97 | 161 | 66 | -66 | -161 | -97 | - | - | - | - | - | - | - | - | - | - | 3.48 | 57 | 87 |
| 7 | 148 | -32 | 6 | 0 | -6 | 32 | -148 | - | - | - | - | - | - | - | - | - | 3.81 | 54 | 81 |
| 8 | 121 | 13 | 84 | 114 | -114 | -84 | -13 | -121 | - | - | - | - | - | - | - | - | 4.09 | 51 | 78 |
| 9 | 27 | -153 | -37 | -24 | 0 | 24 | 37 | 153 | -27 | - | - | - | - | - | - | - | 4.55 | 50 | 73 |
| 10 | 96 | -137 | 167 | 17 | 42 | -42 | -17 | -167 | 137 | -96 | - | - | - | - | - | - | 4.61 | 46 | 78 |
| 11 | 81 | 51 | -106 | 4 | -86 | -0 | 86 | -4 | 106 | -51 | -81 | - | - | - | - | - | 4.97 | 45 | 73 |
| 12 | 99 | 25 | 41 | 126 | -126 | 56 | -56 | 126 | -126 | -41 | -25 | -99 | - | - | - | - | 5.05 | 42 | 78 |
| 13 | 3 | -159 | 7 | 60 | 96 | 74 | 0 | -74 | -96 | -60 | -7 | 159 | -3 | - | - | - | 5.13 | 39 | 79 |
| 14 | -87 | 40 | -62 | 42 | 36 | -89 | -118 | 118 | 89 | -36 | -42 | 62 | -40 | 87 | - | - | 5.24 | 37 | 80 |
| 15 | 3 | 36 | 73 | -47 | -130 | 74 | -175 | 0 | 175 | -74 | 130 | 47 | -73 | -36 | -3 | - | 5.42 | 36 | 80 |
| 16 | 80 | -138 | -67 | 178 | 35 | 0 | 33 | 13 | -13 | -33 | -0 | -35 | -178 | 67 | 138 | -80 | 5.59 | 34 | 81 |

**Table 1:** Optimal slice phase offsets for AM only RF pulse waveforms at a given multiband factor (MBF); $b_{max}$ is the maximum amplitude relative to an equivalent single band pulse. **%MBF** quantifies the relative size of $b_{max}$ compared to MBF, which would be the amplitude for all slices in phase. **%AMFM** quantifies the amplitude reduction achieved by AM only pulses relative to AM/FM. For example MBF=6 results in %AMFM=87, meaning that an AM pulse achieves 87% of the reduction possible using AM/FM.



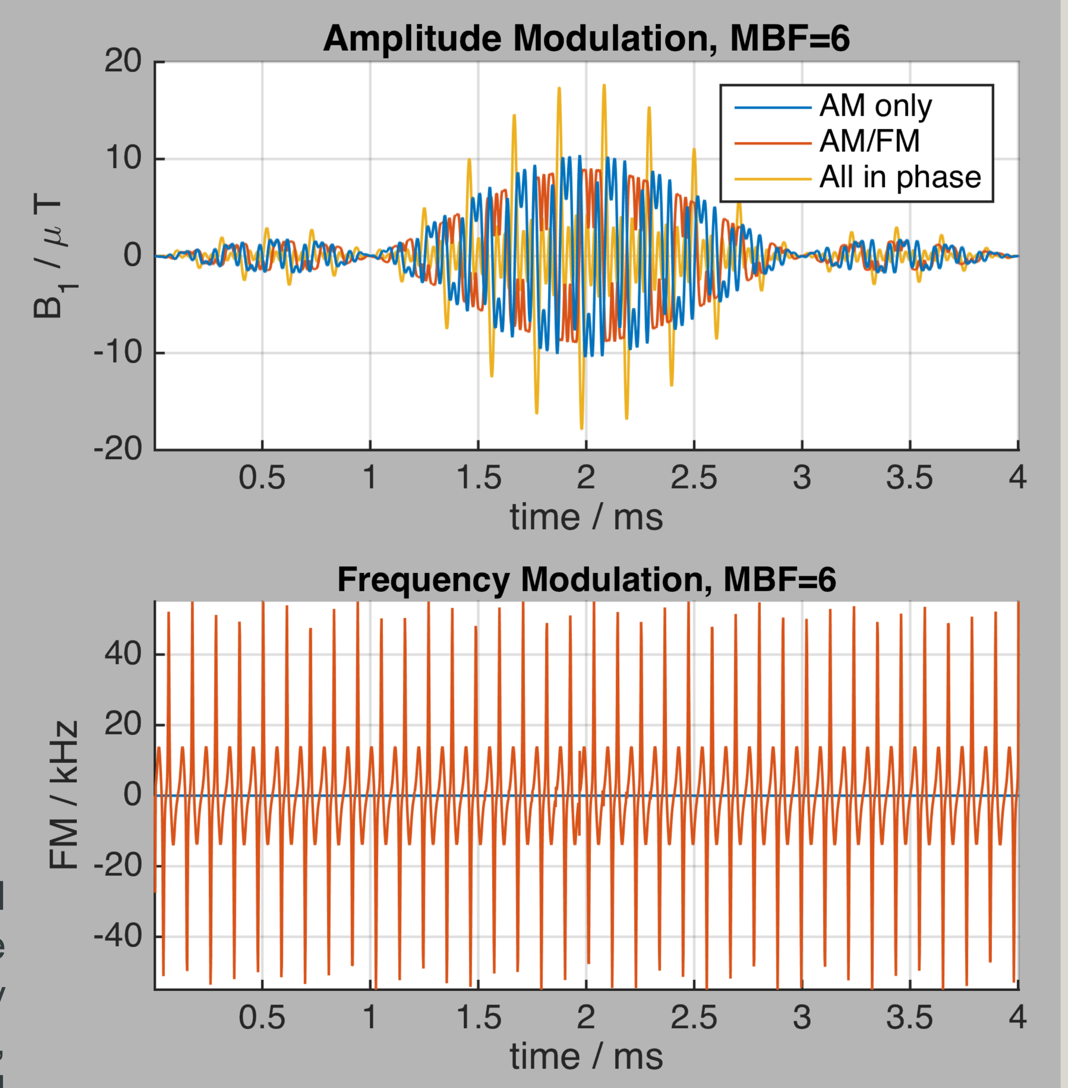




**Figure 1 (above):** $b_{max}$ from AM pulses, compared with AM/FM as proposed by Wong (1). Large reductions in $b_{max}$ compared to all slices in phase are possible using only AM. **Figure 2 (right):** Example amplitude and frequency modulation waveforms for MBF=6, for a TBP=3 selection pulse (thickness 2mm, gap 18mm). AM achieves 87% of the amplitude reduction compared with AM/FM but the latter requires rapid frequency modulation as shown

## Design:

- Form pairs of slices at equal distance |x| from centre (x=0)
- Assign phase offset $\psi$ for each pair such that $\varphi(+x_j)=+\psi$, $\varphi(-x_j)=-\psi$. For odd MBF, slice at x=0 is treated independently
- Find $\psi$ to minimize max{b(t)} using MATLAB's fmincon with 50 random intializations for each MBF.

## Results

Optimized phase offsets are given in Table 1. The table also quantifies the percentage reduction compared with all slices in phase (%MBF) and the relative amplitude reduction from AM only pulses compared with AM and FM together (expressed as percentage, %AMFM). Figure 1 shows performance compared with AM and FM pulses, Figure 2 shows a specific example for MBF=6.

## Discussion

With amplitude modulation only, no improvement is possible for MBF<4. Thereafter the AM solutions reduce $b_{max}$ by an increasing proportion as MBF increases, with reductions over 50% for MBF>8. Relative performance compared with complex waveforms is variable, but %AMFM averages to 80% across all MBFs.

Some factors perform better, for example MBF=6 results in %AMFM = 87% - as Fig.2 shows, the AM only waveform in this case is similar to the full complex solution, but can be achieved without using any frequency modulation.

In other cases (E.g. MBF=9,11) performance is worse, with %AMFM=73%.

The rapid frequency modulation required to realize complex multi-band pulses is sensitive to errors in interpolation and to poor stability. Although not as effective as full complex modulation, **AM only pulses can achieve over 80% of the gains**, while avoiding issues associated with rapid frequency modulation. As a result these have been found to have more robust performance.

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Code: http://mriphysics.github.io

## References

[1] Larkman DJ, et al. JMRI 13:313-317, 2001. [2] Wong E. Proc ISMRM 2012 p2209. [3] Feinberg DA, et al. PLoS one 5(12):e15710, 2010. [4] Auerbach EJ, et al. MRM 69:1261-7, 2013.

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